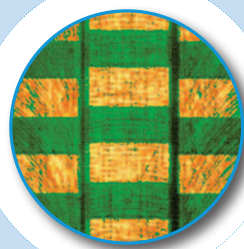
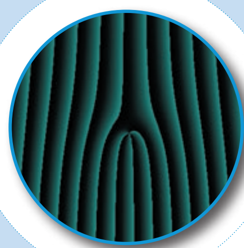
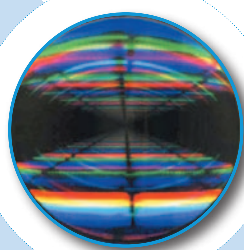
annual report
2011 / 2012

INSTITUT FÜR
TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART



Universität Stuttgart

INSTITUT FÜR TECHNISCHE OPTIK
UNIVERSITÄT STUTTGART

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ANNUAL REPORT 2011/2012

Dear Reader,

another two years filled with many activities in different fields and enriched with fruitful national and world wide cooperation have passed since the ITO staff reported in 2011 about their current research activities. Thus it is again time to inform our partners, sponsors and customers about our recent advances in the field of Applied Optics.

The basic understanding that determines our work remains unchanged: striving for excellence in research and teaching, together with a good balance of continuity and systematic renewing. Ongoing activities are directed at both the profound investigation of our strategic research topics such as multi-scale sensor fusion, computational microscopy, resolution enhancement, model-based reconstruction, asphere and freeform metrology, hybrid optics, digital holography, and optical systems design, and the modernization of our infrastructure. Meanwhile the operation of our reactive ion etching facility has reached the routine level and the Helios Nanolab 600 has been proven as stable and reliable tool for different processing and inspection tasks in the nano world. Our aim to assure flexible structuring technologies with high resolution and reliability not only for a few crucial experiments but for making dedicated optical components is on a good way.

To ensure that ITO can fulfill its mission under changing boundary conditions, we have founded in 2008 the cooperative network SCoPE[1] at the Stuttgart University. The impact of SCoPE is continuously improving and shows encouraging results in the aimed fields: research, teaching and technology transfer. One of the main objectives is the extension of the curriculum in the field of photonic technologies. With the installation of the joint master course in Photonic Engineering, this ambitious goal could be achieved in spring 2013. Scientists from 3 different faculties – physics, electrical engineering and mechanical engineering – are teaching together now the state of the art in Photonics. A continuous increase in students can be observed as a welcome trend. Furthermore, several joint research projects are on the way and the cooperation with our industrial partners is progressing in various fields of common interest.

As a member of the Faculty of Mechanical Engineering, the Institute represents the University of Stuttgart in the field of Applied Optics in research and education. Together with our national and international partners, our research work focuses on the exploration of new optical measurement, imaging and design principles and their implementation in new components, sensors and sensor systems. One of our long-term central goals is the extension of existing limits by combining modelling, simulation and experimental data acquisition in the context of actively driven measurement processes. Several ambitious objectives are still on our agenda such as the implementation of a multi-sensor measurement systems where the systematic cooperation of different classes of sensors is controlled by a sophisticated assistance system, the implementation of our new software system ITOM that helps us to improve the software development for our setups considerably, the completion of the prototype of our new tilted wavefront interferometer with the goal of market launch in 2014, and the further improvement of our model-based strategies for the solution of different kind of identification problems in optical imaging and metrology.

Our overall research approach "Optical Metrology and Systems Design" is structured into ten main research directions:

- Active Metrology,
- Model-based Metrology,
- Remote Metrology,
- Resolution Enhanced Technologies,
- Computational Imaging,
- Sensor Fusion,
- Sensor Integration,
- Hybride Optics,
- Simulation, and
- Optical Systems Design.

The strong interaction between these directions gives the Institute the required depth across the broad range of our activities in optics. The considerable number of research projects that are referred to in this report reflects again the success of this approach.

Besides our wide research activities, an ongoing strong commitment of ITO is directed to high-quality teaching on different levels (bachelor, master, PhD). Our consecutive bachelor-master course in medical technology – a joint and challenging project of the University of Stuttgart and the Eberhard Karls Universität Tübingen – is running very successful and enters now the master level. Since the beginning in 2010, ITO is one of the drivers of that course. In 2011 we started a new master course with the dedication "Mechanical Engineering – Micro, Precision and Optical Engineering M.Sc." and in spring 2013 the mentioned master course "Photonic Engineering M.Sc." has been implemented.

To cope with our ambitious and extensive approach to Applied Optics, a deep understanding of physics needs to be combined with practical engineering implementation. This is a daily challenge for all members of the staff. However, a good mixture of graduates in physics and engineering, a vital and innovative scientific climate, that considers the interdisciplinary cooperation with numerous national and international institutes, and a continuous observation of the technological and scientific progress are a good basis to meet these and future challenges.

Stuttgart, July 2013

Wolfgang Osten

[1] Stuttgart Research Center of Photonic Engineering, http://www.scope.uni-stuttgart.de/

Index

Institute structure

Research projects

3D-Surface Metrology

Active Optical Systems and Computational Imaging

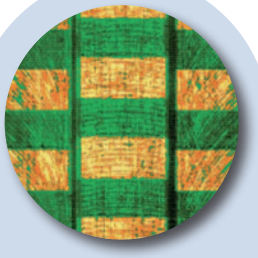
Coherent Metrology

Team and structure

Chair
Prof.Dr. W. Osten
Prof. Dr. A. Herkommer

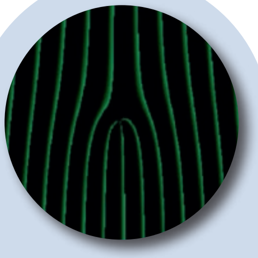
Teaching
E. Steinbeißer

Deputy
Dr. T. Haist



3D-Surface Metrology
W. Lyda

- Macro and micro metrology
- White light and spectral interferometry
- Confocal microscopy
- Fringe projection
- Sensor-models and sensor-fusion

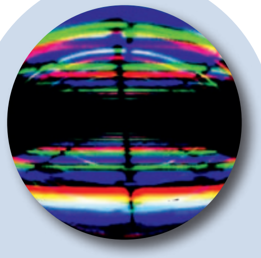


Active Optical Systems
Dr. T. Haist

- Active wavefront modulation
- Active wavefront sensors
- Adaptive optics
- Computational imaging
- Dynamic holography

High Resolution Metrology
Dr. K. Frenner

- High resolution microscopy
- Scatterometry
- Light-surface interaction
- Modeling and rigorous simulation
- Model-based reconstruction



Interferometry and Diffractive Optics
F. Schaal

- Technology and components
- Design and fabrication of diffractive optics
- Interferometry
- Testing of aspheres and freeform surfaces
- Micro-optics

Coherent Metrology
Dr. G. Pedrini

- Digital holography
- Phase retrieval
- Non-destructive testing
- Experimental stress analysis
- Remote laboratories and metrology

Optical Design and Simulation
Prof. Dr. A. Herkommer

- Optical design
- Illumination design
- Optimization methods
- Simulation of imaging- and illumination systems
- Optical systems in medical engineering

Administration, Software Engineering & Technical Support

Staff of the Institute

Status quo: May 2013

Director

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Professorship for Optical Design and Simulation

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Christa Wolf .... left on 31.12.2012

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Scope

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Michael Warber .... left on 31.03.2011
Avinash Burla .... left on 25.03.2012

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Jun Ma .... left on 31.03.2011
René Reichle .... left on 30.06.2011
Eugenio Garbusi............................... left on 31.08.2011
David Hopp....................................... left on 30.09.2011
Dominik Flöß.................................... left on 29.02.2012
Matthias Häfner............................... left on 31.01.2013

Coherent metrology

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Mohammadreza Bahrami................ left on 15.05.2013

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Andreas Lorenz................................ +49 (0) 711 685-66089 .... lorenz@ito.uni-stuttgart.de

Guest Scientists

Dr. Caojin Yuan * .... Univ. of Science and
.... Technology Chenggong (China)................ 12/2009 – 06/2011

Giorgio Pariani................................. Politecnico di Milano (Italy)........................10/2010 – 03/2011

Dr. Francisco Salgado-Remacha .... Universidad Complutense
.... de Madrid (Spain)....................................... 04/2011 – 07/2011

Dr. Vani Chanival .... Parul Inst. of Engineering & Techn.,
.... Vadodra (India) .... 05/2011 – 07/2011

Prof. Benfeng Bai............................. Tsinghua University (China) ....02/2012 – 03/2012

Prof. Anand Krishna Asundi............ Nanyang University (Singapur) ....03/2012 – 04/2012

Pavel Pavlicek .... Palacky University (Czech Republic)...........05/2012 – 06/2012

Dr. Dinesh Naik * .... The University of Electro-
.... Communication (UEC) (Japan)........................... since 06/2012

Prof. Anhu Li .... Tongji University (China) .... 07/2012 – 01/2013

Larbi Bouamama .... Ferhat Abbas University of Setif (Algeria) .. 07/2012 – 08/2012

Dr. Peng Gao * .... Shenzhen University (China).............................. since 09/2012

Henri Partanen.................................. Univ. of Eastern Finland (Finland) ....10/2012 – 11/2012

Huarong Gu....................................... Tsinghua University (China) .... since 01/2013

Ruslan Shimansky............................ IA&E SB RAS Novosibirsk (Rusia) ....01/2013 – 02/2013

Prof. Dr. Mitsuo Takeda ** .... Utsunomiya University (Japan)......................... since 03/2013

** Humboldt fellowship* *** Humboldt prize-winner and stays at the ITO for altogether one year*

Foreign Guests visiting the Institute: 2011 – 2012

Prof. Dr. R. Leach .... NPL, Teddington, UK .... January 2011

Prof. J. Coupland .... Loughborough Univ., UK.................................... January 2011

Prof. Dr. Min Yuung Kim .... Kyungpook National University, Korea...............February 2011

Dr. R. Völk.. SUSS Microoptics, Neuchatel ....March 2011

Dr. Jiri Novak .... Czech Technical University in Prague,
Czech Republic .... May 2011

Prof. Dr. W. Coene .... ASML, Veldhoven, Netherlands .... May 2011

Prof. Dr. Albertazzi .... Univ. Florianopolis, Brazil .... May 2011

Prof. Dr. M. Takeda .... UEC, Chofu, Japan .... May 2011

Prof. Dr. B. Javidi .... Univ. of Connecticut, Storrs, USA .... May 2011

Dr. N. Reingand................................. Patent Hatchery, Baltimore, USA .... May 2011

Dr. C. Gorecki .... Univ. Besancon, France .... June 2011

Dr. Arun Anand .... Institute for Plasma Research, Gujarat, India .... June 2011

Prof. Dr. C. Joenathan...................... Rose-Hulman Inst. of Technology;
Terre Haute, USA...July 2011

Dr. D. Mansfield .... Taylor Hobson, Leicecster, UK ....October 2011

Prof. Dr. F. Mugele .... Univ. Twente, NL .... November 2011

Prof. Dr. P. Bryanston-Cross............ Univ. Warwick, UK... November 2011

Prof. Dr. I. Moreno .... Univ. Alicante, Spain .... December 2011

Prof. Dr. J. Campos........................... Univ. Barcelona, Spain .... December 2011

Prof. Dr. C. Joenathan...................... Rose-Hulman Inst. of Technology;
Terre Haute, USA..Febr. 2012

Dr. P. de Groot................................... Zygo, Middlefield, USA.. May 2012

Dr. Arie den Boef .... ASML Veldhoven, Netherlands .... June 2012

Prof. Dr. C. Joenathan...................... Rose-Hulman Inst. of Technology;
Terre Haute, USA...October 2012

Dr. A. Bernal .... Rose-Hulman Inst. of Technology;
Terre Haute, USA...October 2012

Project partners

Project collaboration with the following companies and organisations
(and many others):

ASML Netherlands B.V.	Veldhoven, Netherlands
Carl Zeiss Microscopy	Jena
Carl Zeiss AG	Oberkochen
Carl Zeiss SMT AG	Oberkochen
Centre Spatial de Liege	Liege, Belgium
Centre Suisse d'Electronique et de Microtechnique	Zurich, Switzerland
DermoScan GmbH	Munich
ESTEC	Noordwijk, Netherlands
FOS Messtechnik GmbH	Schacht-Audorf
Fraunhofer ENAS	Chemnitz
Fraunhofer IOF	Jena
Fraunhofer IAP	Potsdam
Holoeye AG	Berlin
HSG-IMAT	Stuttgart
ILM	Ulm
LaVision GmbH	Göttingen
Mahr OKM GmbH	Jena
Polytec GmbH	Waldbronn
Robert Bosch GmbH	Gerlingen
Shenzhen University	China
Sick AG	Waldkirch
Siemens AG	München
Staatliche Akademie der Bildenden Künste Stuttgart	Stuttgart
Statice	Besancon, France
Trumpf GmbH + Co. KG	Ditzingen
Tsinghua University	Peking, China
Université de Franche-Comté	Besancon, France
University of Eastern Finland	Joensuu, Finland
VTT Technical Research Centre of Finland	Espoo, Finland

Studying optics

Traditionally our curriculum is primarily directed towards the students in upper-level diplom courses of **Mechanical Engineering, Cybernetic Engineering, Mechatronics, and Technology Management**. Since the academic year 2011/12 this courses are offered as Master courses and an increasing number of master students is going to join our lectures.

This applies especially for the new master programme **"Micro-, Precision- and Optical Engineering"** which enjoys great popularity also by students from other universities even from other countries.

Since the academic year 2009/10 we also offer our optics courses within the new bachelor and master program **"Medical Engineering"**, and since 2012 also within the new master program **"Photonic Engineering"**. We also welcome students from other courses, such as "Physics" and "Electrical Engineering" and "Information Technology".

The following list should give you an overview about the lectures given at the ITO. Be aware that not all lectures are suitable for all courses and that the lectures are held in German language.

Core subjects in Master Courses (6 ECTS - Credit Points):

- **Fundamentals of Engineering Optics**
  Lecture: Prof. Dr. W. Osten
  Exercise: H. Gilbergs, E. Steinbeißer

- **Optical Measurement Techniques and Procedures**
  Lecture: Prof. Dr. W. Osten
  Exercise: Dr. K. Körner, E. Steinbeißer

- **Optical Information Processing**
  Lecture: Prof. Dr. W. Osten
  Exercise: Dr. T. Haist, Dr. K. Frenner

- **Fundamentals of Optics**
  Lecture: Prof. Dr. A. Herkommer
  Exercise: D. Rausch

- **Optical Systems in Medical Engineering**
  Lecture: Prof. Dr. A. Herkommer
  Exercise: D. Rausch

Elective subjects in Master Courses (3 ECTS - Credit Points):

- **Optical Phenomena in Nature and Everyday Life**
  Lecture: Dr. T. Haist

- **Image Processing Systems for Industrial Applications**
  Lecture: Dr. T. Haist, Dr. Ch. Kohler

- **Fundamentals of Colorimetry and Digital Photography**
  Lecture: Dr. K. Lenhardt

- **Polarization Optics and Nanostructured Films**
  Lecture: Dr. K. Frenner

- **Introduction to Optical Design**
  Lecture: Dr. Ch. Menke, Prof. Dr. A. Herkommer

- **Current Topics and Devices in Biomedical Optics**
  Seminar: Prof. Dr. A. Herkommer

Additional studies:

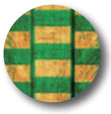
- **project work and thesis within our fields of research**
  (you will find a list of all student project works at the end of this annual report)

- **practical course "Optic-Laboratory"**
  ==> speckle measurement
  ==> digital image processing
  ==> computer aided design of optical systems
  ==> measurement of the spectral power distribution

- **practical course "Optical Measurement Techniques"**
  ==> 3D surface measurement applying fringe projection
  ==> digital holography
  ==> 2D-interferometry and measurement
  ==> quality inspection of photo-objectives with the MTF measuring system

- **common lab for mechanical engineering (APMB)**

The research groups

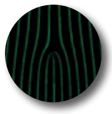


3D-Surface Metrology

The objective of the group is the analysis and the implementation of new principles for the acquisition of optical 3D-surface data of engineering and biological objects over a wide scale. Our main focus is on the enhancement of the metering capacity by a combination of physical models and optimized system design.

Current research activities are:
- 3D-measurement applying fringe projection and deflectometry (macroscopic and microscopic)
- adaptive techniques using spatial light modulators
- confocal microscopy
- white light interferometry
- spectral interferometry
- sensorfusion and data interpretation strategies

Contact: **ofm@ito.uni-stuttgart.de**



Active Optical Systems and Computational Imaging

The objective of our work is the development of flexible optical systems in order to enable new applications, especially within the field of scientific and industrial metrology. To achieve this goal, we make use of different modern light modulation technologies and computer-based methods. One focus of our work lies in the application of holographic methods based on liquid crystal displays and micromechanical systems for various applications ranging from optical tweezers to aberration control and testing of aspherical surfaces.

Main research areas:
- active wavefront modulation and sensors
- adaptive optics
- active wavefront sensors
- dynamic holography
- components, algorithms, and strategies
- waveoptical computing
- computational imaging

Contact: **aos@ito.uni-stuttgart.de**

High Resolution Metrology and Simulation

The goal of this research group is the investigation of the interaction of light with 3d object structures in the micro and nano domain. Along with experimental research, one major aspect is the rigorous modelling and simulation as an integral part of the active metrology process.The analysis of all information channels of the electromagnetic field (intensity, phase, polarisation state of light) allows us to obtain sub-wavelength information about the structure.

Current research areas:

- modelling and rigorous simulation
- computational electromagnetics
- inverse problems
- high resolution microscopy
- scatterometry
- optical metamaterials

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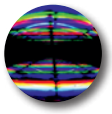

Interferometry and Diffractive Optics

The goal of our research activity is to explore new measurement concepts using diffractive optics. One important application is the testing of optical surfaces, in particular, aspheric lenses. For this purpose we design and produce computer generated holograms (CGH). At the same time, we develop flexible measurement techniques for aspheres and freeform surfaces that aim to replace static null correctors. In addition to CGH for interferometry, our in house production facilities allow us to produce diffractive elements and micro-optics for a wide variety of applications such as imaging systems, UV-measurement systems, beam shaping applications and wavefront sensing.

Our research areas include:

- testing of aspheric and freeform surfaces
- design, fabrication and testing of hybrid refractive/diffractive systems
- interferometry and wavefront sensors
- tailored optics for metrology applications
- fabrication of diffractive optics

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Coherent Metrology

Our research objective is the analysis and application of methods based on coherent optics for the measurement of 3D-shape and deformation and to determine the material properties of technical objects and biological tissues. Aside from the quantitative measurements of form and deformation, methods for non destructive material testing are also analysed and applied.

Research areas include:

- digital holography
- pulsed holographic interferometry
- dynamic strain measurements on biological samples
- shape measurement
- wavefront reconstruction
- holographic non-destructive testing
- endoscopy
- remote and virtual laboratories

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Optical Design and Simulation

Focus of the group is the classical optical design of imaging and illumination systems, as well as ray-based and wave-optical system simulations. Main research targets are the development of novel tools for simulation and optimization and the design of innovative complex optical systems for industrial or medical purposes.

Current research topics are:

- imaging design
- illumination design
- optical simulations (ray-tracing and wave-optical)
- phase space methods in optical design and simulation
- complex surfaces in optical system design
- design and simulation of hybrid optical systems

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RESEARCH PROJECTS

3D-Surface Metrology

Active inspection of three-dimensional objects using a multi-sensor measurement system

M. Gronle, W. Lyda, A. Burla, T. Haist, W. Osten

In the manufacturing process of components with complex three-dimensional surfaces, there is a growing demand for consistent quality control, calling for fast, reliable and flexible inspection systems. Considering complex objects, it is a common insight, that this demand cannot be met in a single measurement step. Instead, different inspection steps have to be applied to different sub-regions on the object. Within these sub-regions, defects with varying characteristics, regarding e.g. their size or their general form, have to be detected and analyzed. In order to realize such a manifold inspection task, a flexible multi-sensor measurement system is implemented. It may consist of a set of different sensors, each having individual properties that are located at different positions in the area of conflict consisting of the resolution, measurement speed and field size.

The focus of the project "AMuPrüf" lies in the development of a flexible inspection system for finding different defects on the surface of small gears. At first, a meshed model of the gear is created based on the common set of parameters, like its module or number of teeth. The surface of the gear can now be split into some main functional sub-regions, where each region must confirm a certain set of specifications. The objective of the overall inspection system is to verify these given specifications. An example might be that no defects of the general type "scratch" must be on the surface whose dimensions exceed a given limit.

In order to realize a successful and flexible system for inspecting varying specifications, the following challenges have to be considered and overcome:

Usually, large areas have to be searched for very small defects. Additionally, the size and shape of each defect may also vary with respect to the type of gear or specification. Due to the limited space-bandwidth-product of optical sensors, it would need a lot of time in order to sample the whole surface with a high-precision sensor. To balance this conflict, a multi-scale measurement strategy with multiple sensors fused in one system is utilized to characterise the surface at different scales. This strategy follows an iterative exploration strategy, where a combination of a coarse scale sampling together with an adapted data analysis (indicator function) provides hints where defects may lie, such that the system only needs to resample these regions of interest with sensors working in finer scales until the final result can be achieved.

A hardware assistant system helps the user to select an appropriate set of sensors including their ideal parameterization for realizing this multi-scale inspection system with respect to the given general task.

Due to the complex surface structure of objects like gears, a high precision positioning system together with an appropriate software package is needed in order to optimally position the object with respect to each sensor. Additionally, an enhanced extrinsic calibration strategy has been developed, such that the relative position of each sensor in one global coordinate system is known. Then, the data sets, acquired at different positions and in different scales, can be merged together in one common system and compared with the given model of the inspected object.

The demonstrator for the inspection of gears is based on a modified Mahr MFU 100 (Fig. 1.) which contains of three translational axes and one axis of rotation. The mounted sensors are one scalable fringe projection microscope (based on a Leica microscope MZ 12.5) whose magnification can be switched between 0.8x and 10.0x. Additionally the sensor in the finest scale is a chromatic confocal point sensor CHRocodile E (Precitec).

Fig. 1: *Automated multi-scale inspection system based on a modified Mahr MFU 100. The coarse sensor scales are covered by a scalable fringe projection microscope while a chromatic confocal point sensor is used for high-precision measurements in the finest scale.*

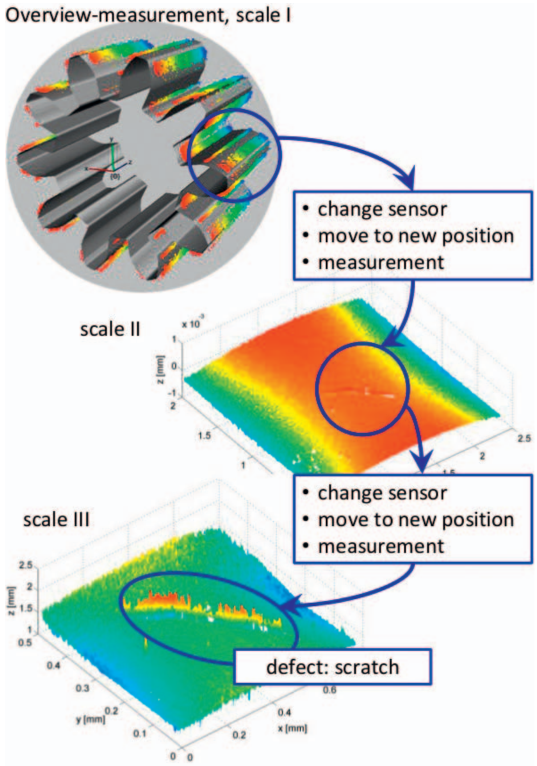

Fig. 2: *Multi-scale inspection cycle for the examination of a scratch on one face of the gear.*

Figure 2 shows an example for detecting a scratch on one face of a gear using the multi-scale inspection strategy. The fringe projection microscope samples the surface with a low magnification in order to obtain a quick overview measurement that is afterwards correlated with a polygonal model of the gear. Based on the model, the faces are indicated and measured again with a more precise sensor. Then, another indicator function marks a sub-regions, where the given specification (here: a scratch on the surface) is possibly not met. By repeating this procedure using the scalable sensor, the final decision is taken in the third scale, where the defect can be clearly resolved and characterized.

For an automatic and optimal definition of appropriate indicator functions, a software assistant system has been developed. The input to this system is a library of real measurement data together with marked defects in each image. Using an optimization algorithm based on genetic programming, a chain of basic image processing steps together with the appropriate set of parameters is selected, such that the marked regions are automatically determined out of the training data set. An example for the indication of a scratch in the intensity image of one single acquisition is depicted in figure 3.

Finally, the actuators, sensors and assistant systems are combined in one complex software, which still is under development and further has to be equipped with a field of view planning in order to optimally position the sensor with respect to the object's surface, considering the shape and local gradient of the object as well as the general visibility of the region by a certain sensor at a specific position.

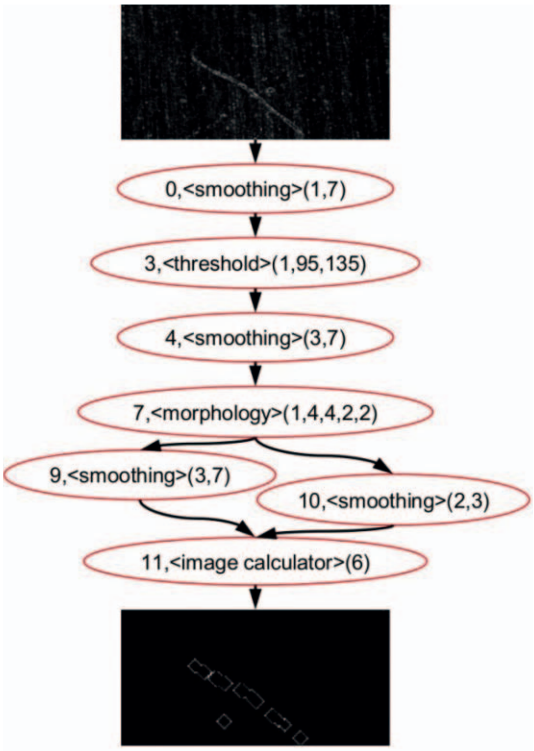

Fig. 3: *Image processing algorithm in order to indicate the position of the scratch in the input image. The algorithm has been created and optimized using genetic programming based on a set of training data.*

Supported by: Baden-Württemberg Stiftung
Project: "AMuPrüf"

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[1] Burla, A.; Haist, T.; Lyda, W.; Aissa, M. H.; Osten, W. „Assistant systems for efficient multiscale measurement and inspection", Proc. SPIE 8082 (2011).

[2] Lyda, W.; Burla, A.; Haist, T.; Gronle, M.; Osten, W. „Implementation and Analysis of an Automated Multiscale Measurement Strategy for Wafer Scale Inspection of Micro Electromechanical Systems", IJPEM 13 (2012).

[3] Gronle, M.; Lyda, W.; Burla, A.; Osten, W. "Extrinsic calibration of a fringe projection sensor based on a zoom stereo microscope in an automatic multiscale measurement system", Proc. SPIE 8430 (2012).

[4] Burla, A.; Haist, T.; Lyda, W.; Osten, W. „Software Assistant System for Automatic Algorithm Design and Configuration in Multiscale Inspection based on Genetic Programming", Opt. Eng. 51(6) (2012).

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Advanced signal evaluation and line sensors for chromatic confocal spectral interferometry (CCSI/LCSI)

T. Boettcher, M. Gronle, W. Lyda, W. Osten

Chromatic confocal spectral interferometry (CCSI) is a hybrid measurement method for fast topography measurement without mechanical axial scan. The CCSI-method combines the advantages of the interferometric gain and accuracy with the robustness of confocal microscopy. A one shot measurement is achieved by using chromatically separated foci in the object space and a spectral detection of the white light signal.

In common used spectral interferometers (SI) the measurement range is given by the depth of focus leading to a restriction of the numerical aperture. The combination of chromatic separation and confocal filtering decouples the measurement range from the depth of focus, which yields higher numerical apertures and improved lateral resolution in comparison to common SI-sensors. The advantage of this method is the single shot retrieval of depth positions by either confocal signal analysis or optical path evaluation. Hence CCSI is qualified for high resolution topography measurements of reflecting and scattering objects.

The discrepancy of the limited axial range in previously reported SI-schemes can be visualised as follows. The reference field contains a planar wave front, while the detection wave front acquires a rigorous curvature, when the object lies beyond the depth-of-focus, if aberration effects are neglected. Optical interference between those two fields leads to a reduced contrast of the modulated spectral signal. In the CCSI-scheme presented here, the axial range of the detector is expanded due to the chromatically-dispersed foci by means of a diffractive optical element (DOE). If the object lies within the dispersed focus spectrum, a sharply focused spectral component gets reflected and this induces a high-contrast wavelet in the spectral domain. The amplitude of this modulation remains constant within the entire range of the optical spectrum employed and the axial range of the detector is decoupled from the limited depth-of-focus.

Fig. 1 shows the current Linnik-type setup, where CCSI can easily be compared to standard Chromatic Confocal Microscopy (CCM), using the same optical components and a shutter to switch the reference arm on (CCSI) or off (CCM). An axial measurement range of 18µm up to 100µm is achieved with 50x/0.8 NA or 20x/0.46 NA microscope objectives respectively, where a spectral range from 810 nm to 870 nm is provided by a Superluminescent Diode (SLD).

As shown in Fig. 2, the evaluation of the wavelets envelope from a CCSI measurement shows the same result as a CCM measurement. Utilizing the interferometric information with a lockin phase evaluation leads to a significantly better result.

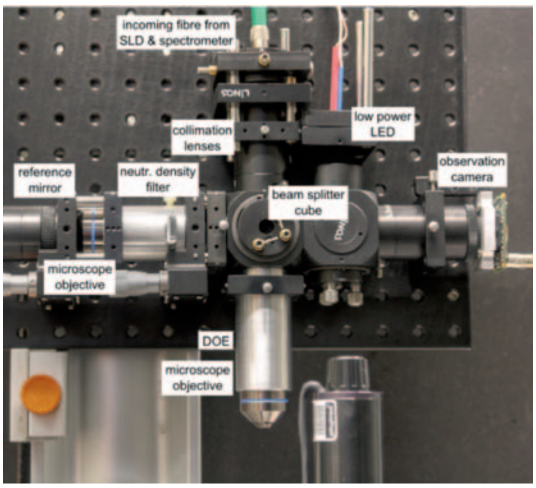

Fig. 1: *Linnik-type demstrator setup for direct comparison of CCM and CCSI.*

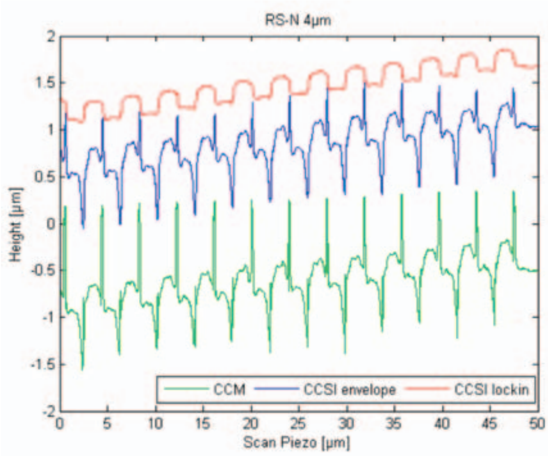

Fig. 2: *Measurement of resolution standard Simetrics RS-N at 4µm pitch with CCM and CCSI, evaluating both, envelope and lockin phase.*

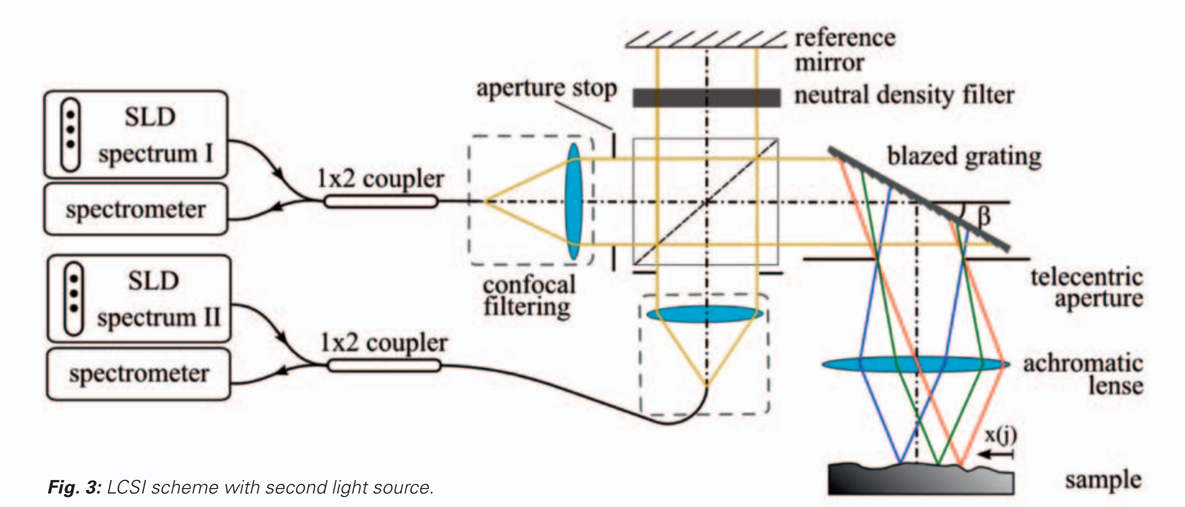

Fig. 3: *LCSI scheme with second light source.*

Furthermore, the Laterally Chromatically dispersed, Spectrally encoded Interferometer (LCSI), a new concept of a one-shot line sensor based on spectral interferometry has been presented. In this design, the spectral separation by a blazed grating leads to a illuminated line of about 1mm length, where every point is spectrally encoded. Thus, the interference signal depends on both, the lateral position and the optical path difference (OPD) induced by the height profile of the specimen. The OPD is usually retrieved from the derivative of the phase term of the signal. In LCSI, for all n pixels of the spectrometer, this derivation leads to a differential equation, which for a single shot measurement can be solved, if a raw estimation on the monotonicity of the phase evolution can be derived from a priori information. Based on first order taylor approximation, one gets n-1 additional equations, leading to a underdetermined system of linear equations. At least one additional equation is needed to retrieve a solution. In many cases, this additional equation can be derived from a simple model of the measured surface, e.g. symmetry considerations. By this approach, precise results can be achieved as shown in Fig. 4.

If the specimen is slightly shifted, every point is illuminated by a second wavenumber, leading to another set of equations. Due to the slight shift, the wavenumber is also only changed by a low value, thus the Signal-to-Noise Ratio drops significantly.

To overcome this limitation, in the current project (DFG OS111/21-3), the LCSI setup will be expanded by a second light source as shown in Fig. 3. The spectral distribution will feature a peak wavelength of 415nm and a bandwidth of about 20 nm. Thus, both light sources can use the same blazed grating for spectral separation. As both light sources provide an independent set of equations, local measurement errors do not globally compromise the result and the measurement principle gets more robust.

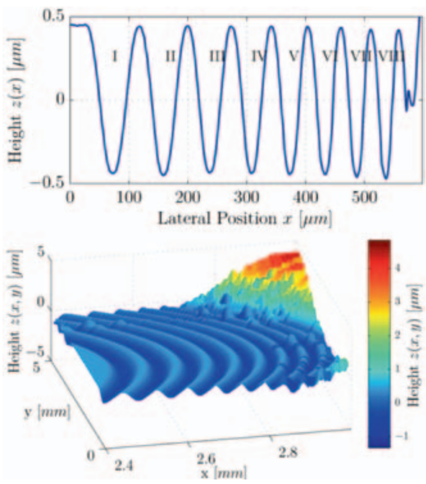

Fig. 4: *Measurement of chirped calibration specimen by PTB with the LCSI sensor. Model based approach without lateral shift is used, axial symmetry assumed.*

Supported by: DFG (OS 111/21-1/2/3)
Project: "Chromatisch-konfokale Spektral-Interferometrie zur dynamischen Profilerfassung"

References:

[1] European patent EP 1 805 477 B1, Interferometrisches Verfahren und Anordnung (2005).

[2] German patent DE 10 2008 020 902 B4, „Anordnung und Verfahren zur konfokalen, spektralen Zweistrahl-Interferometrie" (2008).

[3] Gronle, M. et al. "Laterally chromatically dispersed, spectrally encoded interferometer", Applied Optics 50, 23, 4574-4580 (2011).

[4] Lyda, W. et al. "Advantages of chromatic-confocal spectral interferometry in comparison to chromatic confocal microscopy", Measurement Science and Technology 23, 5, 54009 (2012).

[5] Mauch, F. et al., Improved signal model for confocal sensors accounting for object depending artifacts, Optics Express 20, 18, 19936-19945 (2012).

Design and fabrication of a hybrid hyper-chromatic lens for confocal sensors

W. Lyda, F. Schaal, C. Pruß, W. Osten

Chromatic confocal microscopy is a single shot measurement principle which offers fast, accurate and robust measurement data. In the past years several commercial point and line sensors with submicron accuracy and nanometer resolution for shop floor environment were developed. To take advantage of this high resolution the actuators of the inspection systems have to meet tight requirements on straightness and flatness. The high price of such systems limits their deployment to medium and large production facilities.

The objective of the overall project was to develop an add-on sensor module based on chromatic confocal microscopy for commonly used shop floor microscopes to reduce the necessary capital investment for such type of sensors.

On sub-contractual basis ITO designed and fabricated the hyper-chromatic element for the chromatic dispersion. The element consists of a positive refractive lens and a diffractive optical element (negative Fresnel-lens). By balancing the refraction power of both elements for the center wavelength the measurement range of the sensor is centered around the focal plane of the classical bright field illumination of the system. To switch between classical bright field illumination and point-wise distance measurement mode the element was mounted into the DIC prism revolver of the microscope (see Fig. 1).

The optical element was fabricated at ITO. It is a hybrid diffractive/refractive lens, where the diffractive structures were fabricated on the planar side of a plano-convex lens. Core of our CGH fabrication is the laser writing system CLWS300, a flexible high precision tool that works in polar coordinates, comparable to a DVD writer. This working principle offers the advantage of a high, continuous scanning speed and facilitated fabrication of rotationally symmetric structures. Yet the system is not limited to writing circles but allows to write arbitrary structures such as linear gratings, microlenses or angular scales. It is capable of writing both binary and blazed diffractive optical elements. Blazed structures are written in grayscale mode where the writing beam intensity is varied with at the moment up to 256 levels.

The substrate size can vary from a few millimeters to 300 mm in diameter. The shape can be rectangular, round or any other reasonable outline. The system allows substrate thicknesses up to 25 mm.

The resulting photoresist profile is then either used directly (e.g. for mastering) or is transferred into the fused silica substrate using dry etching (RIE).

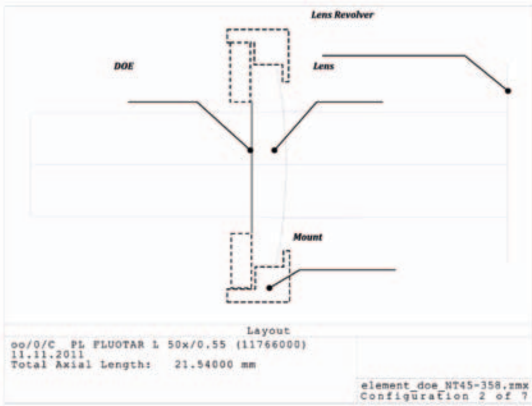

Fig. 1: *Design of the hybrid optical element based on a diffractive optical element with negative focal length and a refractive lens with positive focal length. The combined focal length for the design wavelength is zero*

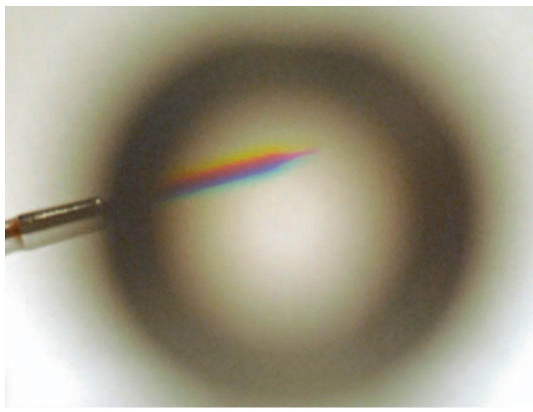

Fig. 2: *Chromatic dispersion of the hybrid element.*

Project: "R&D-Study for ProMicron, Germany"

References:

[1] Körner, K.; Ruprecht, A. "German Patent Appl. DE 103 21 885 A1 (2003)

GPU accelerated ray tracing

F. Mauch, M. Gronle, W. Lyda, W. Osten

Ray tracing is still the most widely used simulation method in designing and analysing macroscopic optical systems. Over the last years several extensions to include diffractive optical elements into ray tracing simulations have been developed, thereby further broadening the application range of ray tracing. However, the fundamental function principle of ray tracing, i.e. propagating light as a set of mutually independent rays through optical systems, implies a nearly perfect linear relationship of computational load to the number of surfaces in the optical system and the number of rays traced through the system. Especially in Monte Carlo based stray light analysis, where a huge number of rays has to be traced non sequentially, this linear relationship is a big issue even on todays computer machines.

Within the BMWi project "Präzisions-Charakterisierung von weißen LEDs und LED-Beleuchtungen" a GPU accelerated ray tracing tool was developed, that utilizes the massively parallel architecture of modern graphic cards to speed up the ray tracing calculations. With this approach it was possible to accelerate the simulation of the spectrometer system that is depicted in Fig. 1 by a factor of up to 50 depending on the number of rays involved in the simulation (see Fig. 2).

This GPU accelerated ray tracing tool, that we call MacroSim, has evolved into a general purpose ray tracing program, that is capable of accelerating both, sequential and non sequential simulations. It offers an intuitive graphical user interface to create a model of the optical system and parameterize the simulation. It can read the popular glass catalogs from Zemax, that describe the optical properties of typical glass materials. Additionally, it is fully integrated in the institutes measurement program "itom", thereby enabling seamless integration of simulated sensor signals into the signal processing chain of real sensor systems.

MacroSim has been released under an open access license according to the popular LGPL license. The source code can be accessed online at https://bitbucket.org/mauchf/macrosim. Therefore we hope that it will find an active community and form the basis for new computation intensive applications of the ray tracing simulation principle.

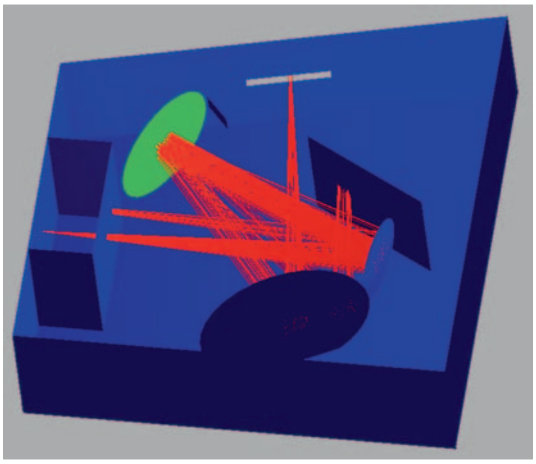

Fig. 1: *Rendered view of spectrometer system as displayed in our GPU accelerated ray tracing software MacroSim. The diffraction grating surface is highlighted in green.*

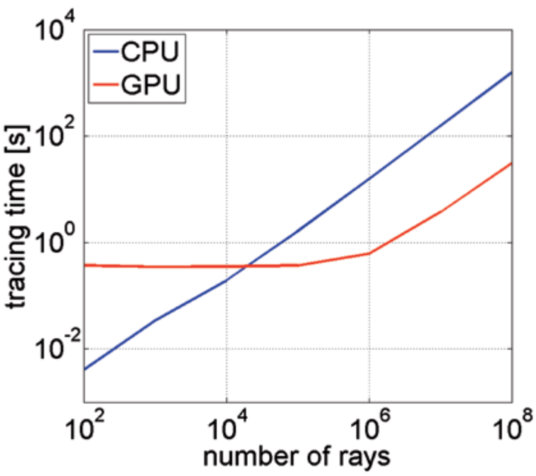

Fig. 2: *Tracing time for spectrometer system in dependence of the number of rays, that are traced. Red and blue lines represent the GPU accelerated and the CPU based code respectively. Note that both axis are scaled logarithmically.*

Supported by: BMBi (FKZ 13N7861)
Project: "PräziLED"

References:

[1] Mauch, F.; Lyda, W.; Osten, W.; Krug, T; Häring, R. "Combining rigorous diffraction calculation and GPU accelerated nonsequential raytracing for high precision simulation of a linear grating spectrometer", Proc. SPIE 8083, 2011.

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Model based characterization of confocal measurement systems

F. Mauch, W. Lyda, W. Osten

The actual form of the microstructure of mechanically highly challenged surfaces determines their functionality and therefore a fast and reliable quality control is crucial for manufacturers of such surfaces. While inspection of such surfaces has been traditionally done with tactile stylus systems, confocal microscopy as well as scanning light interferometry became more and more popular for such inspection tasks over the last years. These systems measure contact free and fast. However they have been characterized in the past mainly on optically smooth surfaces and their behaviour when measuring rough surfaces is sometimes surprising and always depends critically on a number of parameters that can be set by the user of the measurement system, e.g. numerical aperture of the objective etc. This leads to strongly varying inspection results depending on the type of measurement system that was used and the actual parameters that were chosen by the technician, who was doing the measurements.

Therefore, within the BMBF project "Anwenderorientiertes Assistenzsystem zum sicheren Einsatz optischer Abstandssensoren" an assistance system for optical surface measurements is beeing developed. It will assist the user to optimally configure a confocal microscope or a white light interferometer for a specific measurement task. Furthermore, this assistance system will give a traceable estimate of the uncertainty connected to a given measurement.

As a first step we developed an improved signal model for confocal sensors, that is able to predict object depending artifacts. Fig. 2 illustrates such an artefact in a confocal measurement of the PTB chirp calibration standard. We have shown that confocal sensors rely on the fact that the overlap of the illuminating wave-front and the specimens surface is maximum if the specimen is in the focus of the sensor. However, as is illustrated in Fig. 1, for curved surfaces this overlap might become maximum for out of focus positions. This leads to deterministic measurement errors that depend on the particular shape of the specimens surface and results in a lateral resolution of confocal profilometers that is worse than that of confocal imaging devices. Knowledge of this effect will be used to effectively assist the user of confocal sensors when planning measurements and will help to accurately estimate the remaining uncertainty in confocal surface topography measurements.

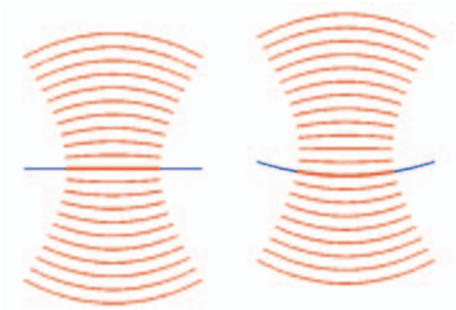

Fig. 1: *Schematic illustration of the improved signal model. Red lines indicate wavefronts of the illumination. The blue line represents the surface of the specimen and the bold red line marks the best matching wavefront for the given surface.*

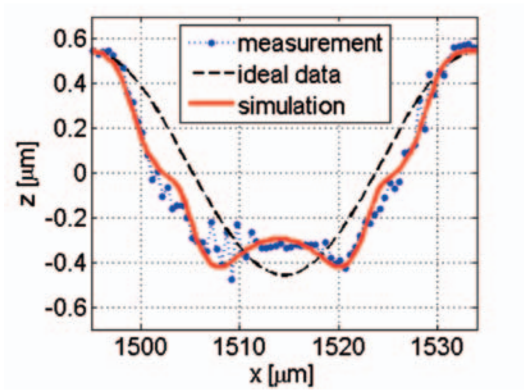

Fig. 2: *Illustrating the good agreement of Simulation and measurement for a chromatic confocal point sensor measurement of the cosine intercept with 39 µm period of the PTB chirp calibration standard. NA for the presented measurement was 0.5.*

Supported by: BMBF (FKZ 13N10386)
Project: "OptAssyst"

References:

[1] Mauch, F.; Lyda, W.; Gronle, M.; Osten, W. „Improved signal model for confocal sensors accounting for object depending artifacts", Opt. Expr., 18, 19936-19945 (2012).

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Optical low-cost sensor system for the control of pump rates

K. Körner, W. Lyda, W. Osten

For the enhancement of a one-way dosing pump, we investigated approaches for the highly resolved optical measurement of the position of the piston, see Fig. 1. The main objective is to ensure a high resolution and a low measurement uncertainty in the rate of fluid delivery from 10 µl/min to 100 ml/min with the same pump module. The industrial application requires both, a very robust and a low-cost solution.

So we applied a low-cost microscopic approach with a small magnification that directly detects the illuminated lip of the moving seal of the pump. For achieving the aims mentioned above, the resolution of the position of the sealing lip has to be in the submicron range. That means sub-pixel accuracy. For this, we use a correlation based method in a sequence of images of the sealing lip for precise detecting the motion of this lip in combination with a Lab-view control loop.

First, we applied a commercially available telecentric lens for detecting the lip position. Fig. 2 shows the calculated movement of the sealing lip in the liquid medium Lipofundin at a pump rate of 5 ml/h, and Fig. 3 presents the calculated mass of the shifted medium over time. Considering linearity, both curves are the same. However, there is a significant difference of about 6% between the optical measurement and the measured mass of a scale. Further investigations showed the not negligible influence of the evaporation of the water content in Lipofundin in our experiments. Another error in measurement is probably caused by synchronization problems of Labview during load stroke of the metering pump.

Secondly, we designed, manufactured and tested a telecentric optical stage with two diamond turned lenses made of acryl glass (PMMA) for proving a low-cost approach for mass production. First results show the technical applicability of that approach.

A very first market analysis of the necessary sensor components including LED illumination and microcontroller provided evidence: The costs for the whole sensor system will not exceed 100 € in case of mass production (1000 sensors a year).

There are widespread application fields for this technical concept also where aggressive fluids have to be used, for example in medical care, chemical industry, biotechnology or pharmacy.

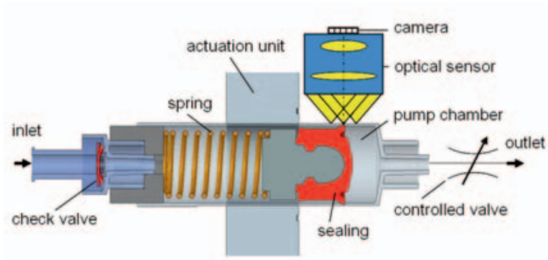

Fig. 1: *One-way pump element (syringe) with an optical low cost sensor (courtesy of HSG-IMAT).*

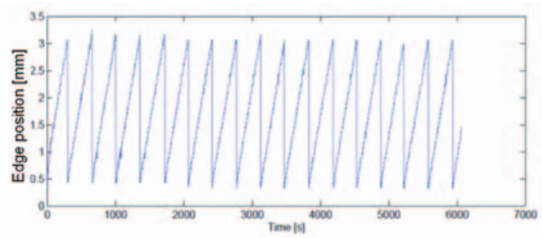

Fig. 2: *Optically detected and by a Labview program calculated shift of the sealing lip in the liquid medium Lipofundin, pump rate 5ml/h. (pump system: HSG-IMAT).*

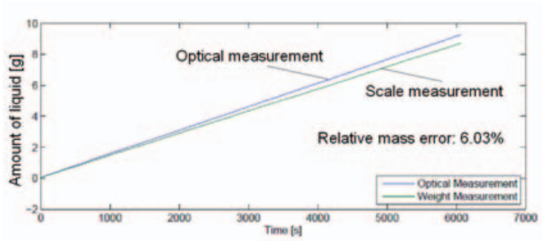

Fig. 3: *Calculated mass over time of medium Lipofundin, pump rate 5ml/h (pump system: HSG-IMAT).*

Supported by: AIF, IGF-No.: ZN09560/09,
ITO project No.: 16653 N
Project: "Optical measurement system for estimation of the position of the piston in a one-way dosing pump"
Project partner: HSG-IMAT

References:

[1] Wolter, F.; Fritz, K.-P.; Kück, H.; Körner, K.; Lyda, W.; Burla, A. "Sensor-controlled metering pump with disposable pump unit", Proc. of the ACTUATOR, Bremen, 2012.

"itom" – measurement and laboratory automation software

M. Gronle, C. Kohler, M. Wilke, W. Lyda, H. Bieger, W. Osten

Both the development of new optical sensors and the operation of such systems for instance in a laboratory environment require a fast and flexible software system. This software has to be able to communicate with a wide range of different hardware systems, such as cameras or actuators and should provide a diversified and as complete as possible set of evaluation and data processing methods. Additionally, the rapid prototyping of modern measurement and inspection setups requires a system, where parameters or components can easily be changed at runtime, necessitating the availability of an embedded scripting language. Finally, when operating a measurement system, it is also desirable to extend the graphical user interface by system adapted dialogs and windows.

Since no commercial software system fits all these requirements within the desired performance and quality parameters, a group at ITO started to design and program the new measurement software "itom" in 2011, partially inspired by the former ITO-software "m".

It mainly consists of four pillars:

1. The core application with its graphical user interface (GUI) gives access to the most important functions of "itom" without further need for scripting or programming any code.

2. The plugin system. The main idea behind "itom" was to keep the core application thin. Therefore, "itom" can be extended by external libraries (plugins), that are dynamically loaded at runtime . One group of plugins provides access to any hardware systems "itom" should be able to communicate with. Other plugins contain data processing and analysis algorithms as well as complex user interfaces like windows or dialogs. The last group of plugins provides plotting and figure components in order to show live images of cameras or visualize other data structures.

3. The popular and powerful scripting language Python is embedded in "itom". It is possible to use Python and the functionalities provided by such freely available modules as Numpy, Scipy or Matplotlib, within "itom". Additionally, a Python-module itom acts as an interface to the core application "itom" as well as its plugins. The scripting system provides full development functionality, including language support and debugging.

4. Measurement systems can be extended by their own GUIs. A WYSIWYG design tool is available, allowing connection of interface elements to scripted functionalities. As a result, users can configure the appearance of their measurement system to optimally enable or protect the underlying functionalities.

The application "itom" itself is programmed in C++ using the open source framework Qt. This framework enhances the functionality of C++, mainly by providing a cross-platform GUI, allowing "itom" to run on both Windows and Linux operating system. The design of "itom" focuses on the support of modern, multi-core processors by making extensive use of multi-threading, effectively running script execution, hardware control and algorithmic plugins each in their own separate threads. As a result, computationally demanding algorithms can be executed or an actuator can slowly move while the main application is still kept reactive.

The core application of "itom" is released under the open source license LGPL. The sources can be freely downloaded from the internet at **https://bitbucket.org/itom.**

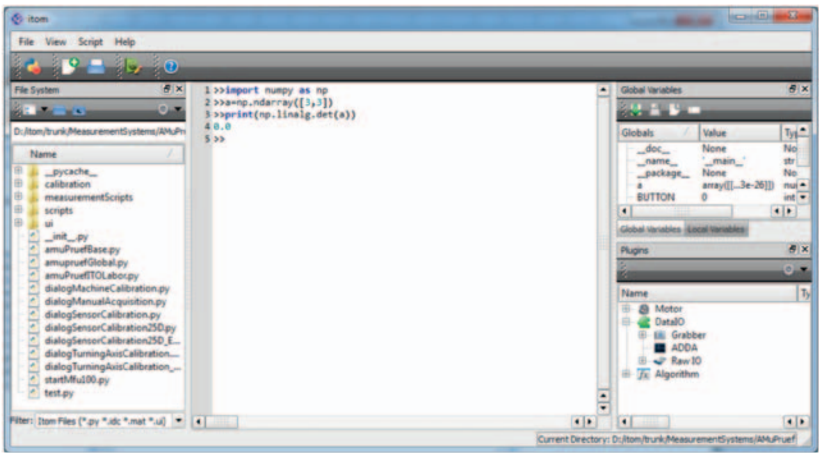

Fig. 1: *Screenshot of itom software on a Windows operating system.*

Vertically integrated array-type mirau-based OCT system for early diagnostics of skin cancer (VIAMOS)

W. Lyda, T. Boettcher, J. Krauter, W. Osten

Skin cancer is one of the most commonly diagnosed type of cancer with an increasing number of cases in the last years. Most cases are caused by over-exposure to UV-light. If the cancer is untreated, it becomes fatal. If the cancer is diagnosed in an early state, it can be treated effectively. Hence an efficient and easy-to-use diagnostic tool is necessary.

The current state of the art is a visual inspection either by clinicians or self-examinations. If cancer is assumed, the potential melanoma is removed and a traditional biopsy is applied as a reference diagnosis. The drawbacks of this technique are the long diagnosis time of several days to weeks and the invasiveness of the procedure, but the advantages are a good image quality and high contrast between malign and belign tissue. Hence non-invasive imaging methods have been developed.

Two methods which match the requirements on the resolution are confocal microscopy and optical coherence tomography (OCT). Both offer a resolution down to some microns and sufficient penetration depth. They offer a non-invasive 3D-visualisation of the human skin. While confocal microscopy offers a higher resolution, OCT has a higher penetration depth along with a short data acquisition time.

The disadvantage of the current systems is the high system cost up to 100 k€, limiting the application to bigger hospitals.

The project VIAMOS aims to reduce the cost of such OCT systems dramatically. Therefore a small handheld, low-cost, OCT device will be developed which is 10 times cheaper and 150 times smaller than current systems. This will be achieved by modern 3D-packaging techniques and direct integration of waver level optics and micro mechanical optical systems like the system architecture based on a parallel Mirau layout developed in the EU-project "Smarthies". The targeted measurement volume is 5 mm x 5 mm x 0.5 mm with an acquisition time under 20 seconds. The challenge will be to cope with the low contrast between different kind of tissue compared to biopsy.

The project consortium brings together academic institutions, research institutes and industrials partners, experienced in the field of MEMS & MOEMS, photonics & OCT, microscopy, system integration and dermatology.

More information under **www.viamos.eu**.

Fig. 1: *VIAMOS-Logo*

Supported by: EU (Call FP7-ICT-2011-8).
Project: "Vertically Integrated Array-type Mirau-based OCT System for early diagnostics of skin cancer"
Project coordinator: Prof. Christophe Gorecki, FEMTO-ST/ Université de Franche-Comté, France

Project consortium:
- *Institute FEMTO-ST, UFR Sciences Médicales et Pharmaceutiques, Université de Franche-Comté, France*
- *VTT Technical Research Centre of Finland.*
- *Institut für Technische Optik, University of Stuttgart, Germany*
- *Fraunhofer-Einrichtung für Elektronische Nanosysteme, ENAS, Chemnitz, Germany*
- *Swiss Center for Electronics and Microtechnology, CSEM SA, Switzerland*
- *DermoScan GmbH, Regensburg, Germany*
- *Statice, Besançon, France*

In-situ surface metrology: Integration of a white light interferometer into a high precision grinding machine for diamond tools

W. Lyda, R. Berger, D. Fleischle, W. Osten

Diamond tools are used to fabricate sophisticated optical surfaces on plane and curved substrates. One production technology is for example fly-cutting for ultra-precision turning and grinding. By these techniques the shape of the Diamond tools are often directly transferred onto the substrates. For example, such tools are needed for the production of micro lens arrays, lenticular screens or intraocular lenses. However, the fabrication of high precision optical surfaces on such substrates is limited by the supply with commercial Diamond tools. The limitation is the ability for the production of accurate and precise tools. Most diamond tools are fabricated by grinding and polishing. But the measurement of the produced tools is carried out after the fabrication process. Due to a tight tolerance zone, there can be a high rate of waste.

In the BMWi InnoNet-project iTool, eight project partners from industry and research institutes worked together to develop a six-axis machine with an integrated optical measurement system for the manufacturing of freeform Diamond tools (see fig. 1). The manufacturing process is intermitted by several measurement cycles. The results of the measurements have to be compared with the required geometrical design form of the Diamond tool to be produced. Then a dataset with new control parameters will be transferred to the six-axis manufacturing machine.

The in-situ concept for an optical measurement of the Diamond tools on the production machine consists of the selection of an appropriate measurement principle and the development of a measurement procedure. Our choice is a combined system, which uses digital image processing and white-light interferometry (see fig. 2). The basis for this system is a MarSurf WS1 white-light interferometer from the Mahr GmbH. A separate LED-illumination is mounted in front of the optical measurement system to have a transmission light device for the visual inspection tool.

The visual inspection tool with the transmission light device is used for the measurement of Diamond tools with a small radius, since their tool flank does not reflect enough light back to the objective, when this part of the Diamond tool is illuminated through the objective. At Diamond tools with a bigger radius and with sections of plane tool flanks, the white-light interferometer can be used to get measurement results with a resolution in the nanometer range. For example, the shape of the cutting edge can be extracted from the topography measurement, since this parameter is an intersection of the 3D-shape of the measured Diamond tool. To acquire all data points along the tool flank, the point clouds of several topography measurements, achieved by the white-light interferometer, are automatically stitched together.

Fig. 1: *Six-axis machine with an integrated optical measurement system (source: IPT, Aachen).*

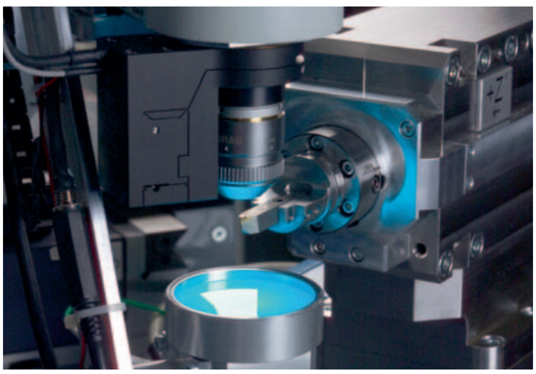

Fig. 2: *Optical measurement system consists of a white-light interferometer with a transmitted light device for digital image processing (source: IPT, Aachen).*

In Fig. 3, a measurement of a diamond tool is shown. This measurement was obtained with digital image processing by edge detection. To sample the whole object it was necessary to obtain a stitching of several measurements. To estimate the vertex radius of this tool a fitting of a circle was obtained. Thus a value of 1,023 mm was determined for that radius.

However, the measurement is obtained by the use of the axis of the production machine. This axis has a certain error. But if a precise measurement has to be obtained, the implied error due to axis uncertainty has to be known. Therefore a simulation investigation into the resulting standard deviation in the measurement depending on the uncertainty of the machine axis has been implemented. In Fig. 4, the results of a simulation are shown.

Future work will investigate the reliability of the complete measurement system and its actuators in respect to the environment. Furthermore a complete automation of the measurement procedure is desirable.

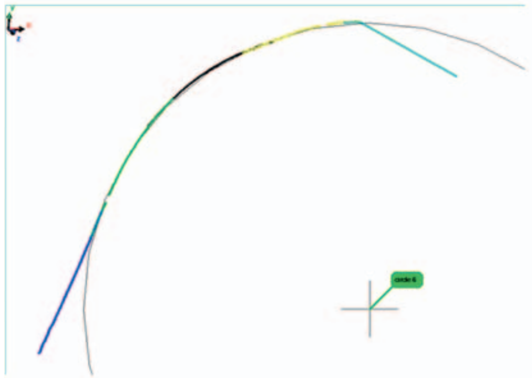

Fig. 3: *Stitched measurement of a diamond tool and fitting of a circle to estimate vertex radius.*

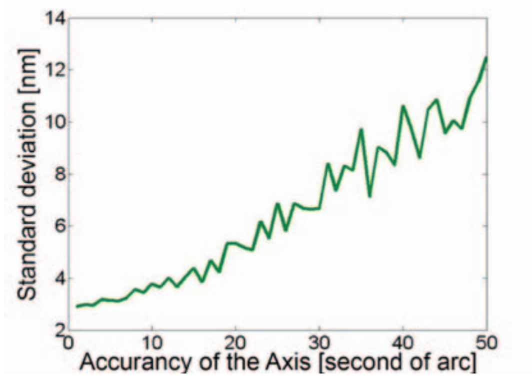

Fig. 4: *Simulation of resulting standard deviation in measurement depending of accuracy of machine axis.*

Supported by: BMWi (FKZ 16IN0519)
Project: "iTool"
Project partner: Fraunhofer Institut für Produktionstechnologie, Aachen; Mahr GmbH, Göttingen; IMOS Gubela GmbH, Freiburg; UPT-Optik Wodak GmbH, Nürnberg; Diamant-Gesellschaft Tesch GmbH, Ludwigsburg; LT Ultra-Precision Technology GmbH, Herdwangen-Schönach

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Active Optical Systems and Computational Imaging

SLM-based vibrometry

T. Haist, C. Lingel, M. Warber, W. Osten

Within the BMBF project "Holovib" different uses of spatial light modulators for heterodyne-based vibrometry have been examined. The elements are used for beamforming and beam-scanning. The main focus are a) single-point scanning systems, b) dynamic multipoint systems, and c) methods for avoiding speckle-induced loss of signal. In the period 2011/2012, especially multipoint vibrometry has been investigated. In cooperation with Polytec, a 14-channel system has been developed (5 MHz heterodyne frequency, $\lambda = 532$ nm). The central element is a spatial phase modulator (Holoeye Pluto, 1920 x 1080 pixels, 8 µm pixel pitch, 2π phase modulation). The system uses one of the two halves of the light modulator for displaying a Fourier hologram, which leads to the generation of the measurement points on the object. The detection hologram is written into the other half of the modulator. By this detection hologram, the light reflected/ scattered at the object is directed onto individual photodetectors. There, the superposition with the reference leads to the measurement signal. The design has been done in Zemax (light scattering analysis in ASAP) and resulted in a diffraction-limited performance over the whole object field.

One of the main challenges of such an approach is to avoid that one of the unwanted diffraction orders might also fall onto a detector. When using a complex superposition of the sub-holograms (advantage: achieving a large aperture and thus a small measurement spot), a lot of unwanted orders will be present (approximately 10,000 to 100,000 orders). With an appropriate combination of hologram optimization and mechanical apertures it is possible to avoid that they cause a signal at the detector.

The main problem of all techniques for multipoint vibrometry is the loss of signal when working on scattering surfaces. Even when using shot noise limited electrons and strong coherent gain the signal to noise ratio is strongly reduced. Regardless of the concept, when using N channels a decrease in signal intensity by 1/N2 will result. This problem can be partially offset by an increased laser intensity or an increase of the total pupil area. Unfortunately, the pupil area is finally limited in the spatial light modulator-based system by the number of pixels in combination with the desired maximum object field (area and maximum deflection angle are coupled via a telescope).

As a result, the experimental setup in the project (20 mW laser source) currently is limited to a simultaneous measurement of 4 channels. Within an additional static system we could improve on this by increasing the total aperture. This comes at the cost of losing the programmability of the positions of the measurement spots. The measurement positions are realized by purely manual means. Appropriate static holograms for collimation and beam splitting have been optimized, manufactured and characterized.

For the optimization of speckle-induced signal reduction, an OKO 37 channel membrane mirror has been characterized and a suitable control software in C++ has been implemented. Based on a phase-shifting Twyman-Green interferometer, influence functions of the mirror have been measured. A reconstruction matrix has been computed, which directly allows a control of the mirror using Zernike coefficients. The system has been used by the University of Wuppertal (Lehrstuhl für Automatisierungstechnik/ Regelungstechnik, Prof. Tibken) for the realization of optimization algorithms. The determination of the best suited modes for controlling the mirror was determined at ITO by simulation of corresponding corrections.

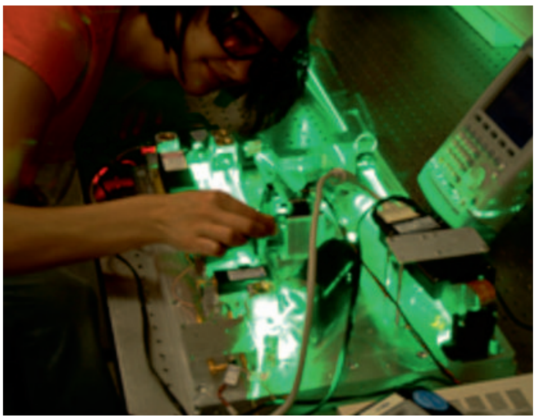

Fig. 1: *Student when aligning the SLM-based multi-point vibrometry system.*

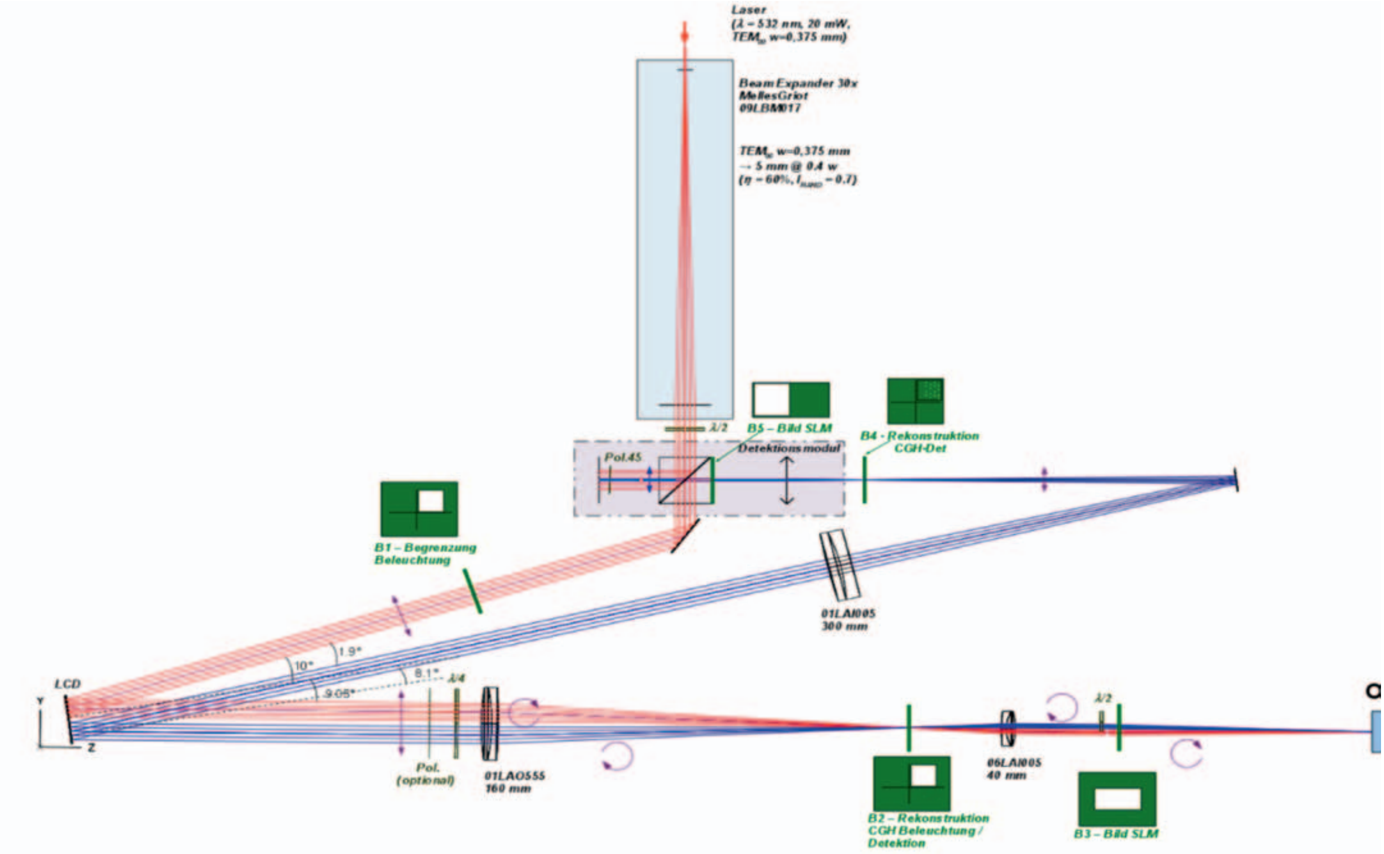

Fig. 2: *Setup for multipoint vibrometry using programmable object positions.*

Supported by: BMBF (13N9339)
Project: "Holovib – LC-basierte holografische Strahlsteuerung für flexible Vibrometriesysteme"

References:

[1] Haist, T.; Lingel, C.; Osten, W.; Rembe, C.; Winter, M.; Giesen, M. "SLM-based Multipoint Vibrometry," in Optical Sensors, OSA Technical Digest 2012, paper SM2F.1, (2012).

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Optimizing the diffraction efficiency of SLMs: Jones matrix simulation model and time dependent variations

C. Lingel, M. Hasler, T. Haist, W. Osten

The aim of the DFG Project "Examination of pixelated spatial light modulators for the reconstruction of digital holograms II" was to characterize the so called fringing field effect and to improve the diffraction efficiency of spatial light modulators (SLM) by taking the measurement results into account.

To achieve this we first measured the Jones matrices with subpixel resolution using two optical setups. The first one is shown in Fig. 1 and is used to measure the phasereduced Jones matrices. It consists of two lenses f1 and f2 which image the magnified SLM onto the camera. Using different configurations of the two polarizers and the quarter wave plate we recorded 15 different intensity distributions. After comparing the measured intensities with 15 simulated intensities and running a simulated annealing optimization we obtain the phaser-educed Jones matrices of the SLM with subpixel resolution. By an interferometric setup it was possible to measure the dynamic phase and therefore to complete the Jones matrices.

Using different subpixel Jones matrices from many different gray value steps as a lookup-table, it was possible to simulate the fringing field effect of blazed gratings and calculate the diffraction efficiencies. By changing the gamma curve of the SLM it was possible to optimize the diffraction efficiencies in the simulation, applying a simulated annealing algorithm, for different blazed grating periods (3 pixel to 10 pixel) for horizontal and vertical directions. To prove the results the diffraction efficiency of the real SLM was measured and it turned out that there was an improvement of the efficiency (for some cases about 10%) for the small periods but not for the large. This is due to the fact, that the fringing field effect for larger periods does not have such a significant influence because the step size between the pixel values is smaller.

It also turned out that there is a strong dependence of the diffraction efficiency on the pulse width modulation (PWM) of the SLM. Fig. 2 shows the time dependent diffraction efficiency of a 4 pixel blazed grating realized with different PWM types, measured with a photodiode. It clearly shows the complex behavior of the diffraction efficiency of the SLM.

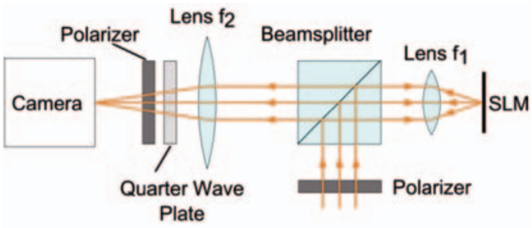

Fig. 1: *Optical Setup for measuring the phasereduced Jones matrices of the SLM with subpixel resolution.*

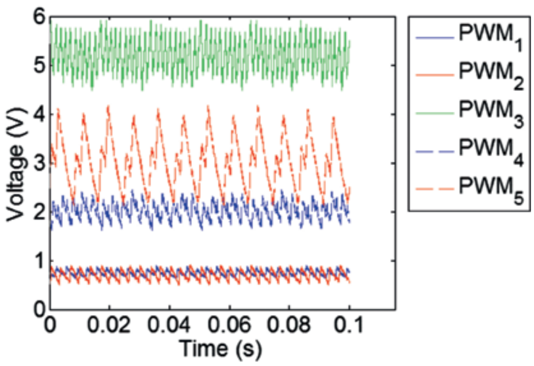

Fig. 2: *Time dependent diffraction efficiency (Voltage of Photodiode) of a blazed grating (4 pixel period) with different PWM methods (given by the constructor of the SLM).*

Supported by: DFG (OS 111/23-2)
Project: "Untersuchung zur Ansteuerung pixelierter räumlicher Lichtmodulatoren für die Rekonstruktion digitaler Hologramme II"

References:

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Fast detection of wavefront disturbance: Holographic modal wavefront sensor

S. Dong, T. Haist, W. Osten

The rapid measurement of wavefronts is necessary for many tasks in the field of adaptive optics. Usually Shack-Hartmann sensors are employed. Unfortunately, at high speed such approaches typically become expensive due to sampling and data processing.

An interesting alternative is to use modal wavefront sensors. In order to detect a certain aberration mode a hologram is used, which encodes the corresponding mode. Illumination of the hologram with the mode leads to two spatially separated spots and by measuring the intensity of these spots using photodiodes one can determine the strength of the mode (see Fig. 1). For the detection of multiple modes, a multiplex hologram is employed and the detectors are placed at the pre-designed positions for the evaluation of each mode (see Fig. 2). Since a thin hologram is used to deflect the light, this sensor is limited to applications where the light source is monochromatic. For small aberrations, the accuracy of the wavefront determination is very good. The more modes to be measured are contained in the wavefront, the greater the crosstalk between the individual holograms and therefore the less accurate are the results of the wavefront determination.

If appropriate design parameters are employed and the whole sensor is used within an iterative correction loop, within a few iterations a sufficiently good optimization of the wavefront can be achieved. Within the project appropriate sensors were optimized for the detection of atmospheric aberrations and tested in a closed-loop adaptive optics system. We also plan to investigate the new concepts by combining the traditional Shack-Hartmann sensing and modal wavefront sensing. The aim is to realize a fast but inexpensive wavefront sensor concept in which different functions are encoded in a single hologram.

The work is performed in close cooperation with the Institute for System Dynamics (ISYS, Prof. Sawodny). A holistic view of the overall correction, consisting of wavefront measurement, control and wavefront modulation, and we hope to improve the performance of an adaptive optics system.

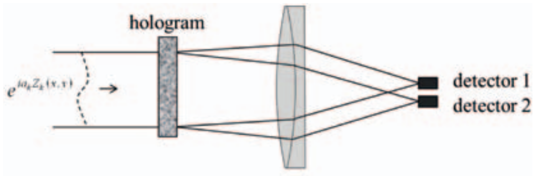
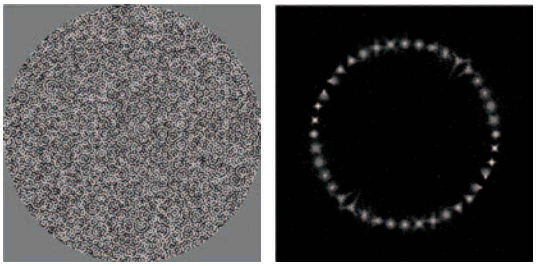


Fig. 1: *Basic principle of measuring magnitude of single Zernike mode in HMWS.*



(a) *(b)*

Fig. 2: *Binary-phase hologram of the HMWS (a) (transmission values: white 1, black -1, grey 0) and its diffraction pattern (b).*

Supported by: DFG (OS 111/29-1)
Project: "Systemanalyse und Methoden zum Reglerentwurf für verformbare Sekundärspiegel in der Adaptiven Optik"

References:

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Programmable microscopy

M. Hasler, M. Warber, T. Haist

In the course of the DFG-project "Propupil" we investigate the opportunities of computa-tional microscopy. Through introduction of a spatial light modulator (a Holoeye Pluto LCD with Full-HD resolution) into the imaging branch of a microscopic setup, we were able to create improved flexibility and user-friendliness in the microscope's capabilities. By placing the LCD in a plane conjugate to the Fourier plane it is possible to apply digital Fourier filters. These filters can be used to realize classical microscope techniques such as Zernike phase contrast or differential interference contrast, which conventionally are achieved by partly intricate alterations in the respective microscope setups, by displaying complex patterns on the LCD.

The flexibility of the LCD also allows for superposition of different patterns, virtually allowing to crossbreed microscope techniques, whose combination in a traditional physical setup would be laborious if possible at all.

Additionally the LCD enables the microscope to correct for optical aberrations that might be introduced into the setup by any means. These adaptions allow the setup to achieve diffraction limited imaging.

Another application can be achieved by diverting the light falling onto the display onto two different images in the camera plane. Since the LCD-plane is an image plane of the entrance pupil, we are able to interpret the directional differences in the twin images to retrieve 3d information for stereovision on the object.

In order to increase the capabilities of the microscope, an additional illumination was installed that can be controlled in the same way as for the imaging. To achieve this, the LCD is divided into two halves and while one half is programmed to control the imaging pathway, the other is employed to use computergenerated holograms for coherent illumination. This is possible without any substantial loss due to the wide 16:9 format of the display.

Additionally, this allows for the implementation of a confocal measurement technique. Through simultaneous defocusing in both holograms a scanning focus spot on an object can be achieved and imaged properly.

Some results are shown in figure 1, displaying a number of images recorded of the same object, with different microscope techniques.

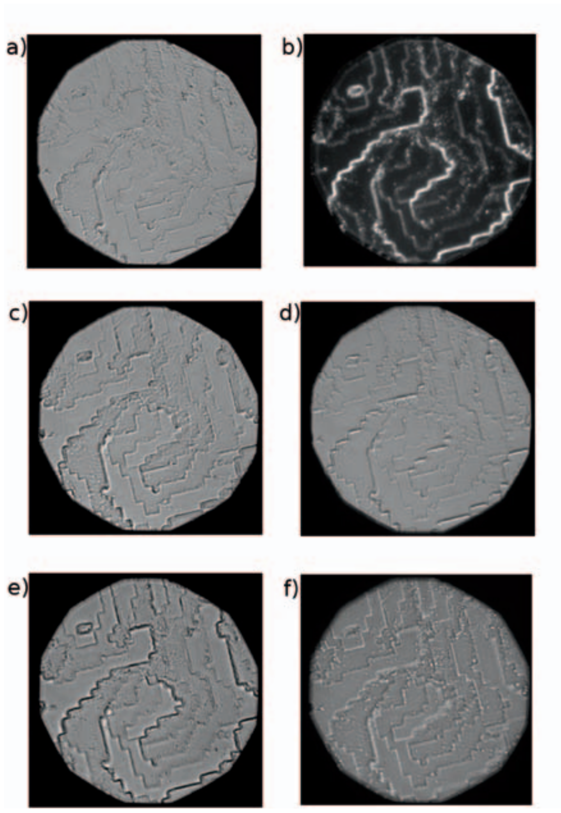

Fig. 1: *A number of images of a CGH taken with different microscopy techniques: a) Brightfield b) Darkfield c) V-DIC d) W-DIC e) V-DIC+Phaseshift f) Zernike.*

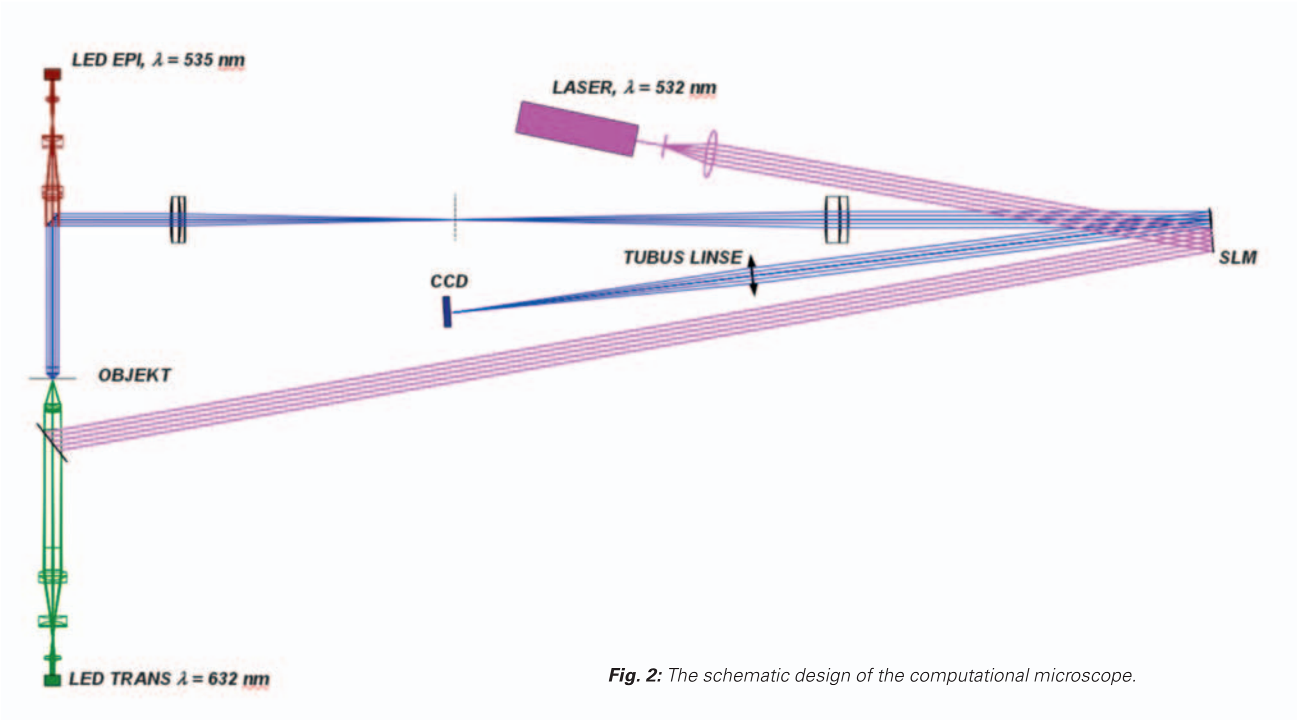

Fig. 2: *The schematic design of the computational microscope.*

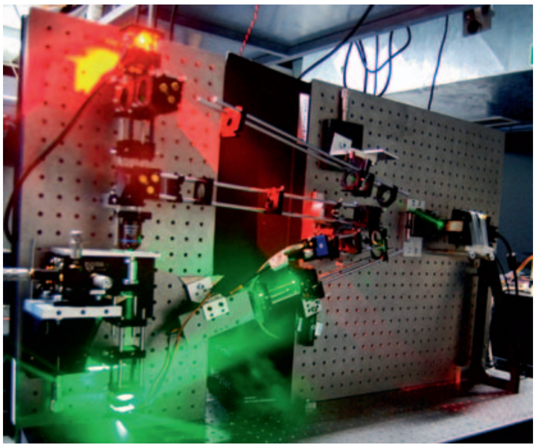

Fig. 3: *An image of the microscope with simultaneous illumination.*

Supported by: DFG (HA 3490/2-1)
Project: "Programmable Microscope Techniques based on light modulator aided Pupil Manipulation"

References:

[1] Hasler, M.; Haist, T.; Osten, W. „Stereo vision in spatial-light-modulator based microscopy", Optics Letters 37, 2238-2240 (2012).

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A systematic method for the description of optical inspection tasks

V. Erdogan, W. Osten

Within the last years the increase of competition and rapid industrialization of automotive industry caused a higher requirement of automation production systems. In this aspect, the visual quality control systems take their place in order to make an important contribution for flexible production systems. Nevertheless, the diversity of optical inspection tasks with different challenges, the increased complexity of processes with short production cycles, the rapid development of visual inspection systems in order to be competitive, specimen of different materials, forms, manufacturing processes and functional requirements and the inspection fea-tures with a wide range of application and function area are not conducive to finding solutions for such tasks, especially for automated surface inspection.

In this work, a systematic method for the description of specific and complicated visual inspection tasks has been developed. The method is designed according to a hierarchical structure: the classification of the inspection object, the inspection task, relevant features and the selection of the inspection sequence. Especially, the inspection features, here the surface defects, are in the focus of this work and plays hereby the key role. The description of surface defects is based on two main parts. In the first part, the defects will be characterized with respect to certain criteria like occurrence, form and appearance. Based on this, in the second part, a mathematical description of the defects takes place in form of the classification in several steps.

For the verification of the developed method diverse experiments on the technical surfaces of a die-cast aluminium part in the automotive industry have been conducted. The goal has been the creation of a detailed and documented catalogue of possible kinds of defects on the technical surfaces of the powertrain. It includes 21 defect types with between 5 and 10 pieces for each defect type. Some examples are shown in Fig. 1.

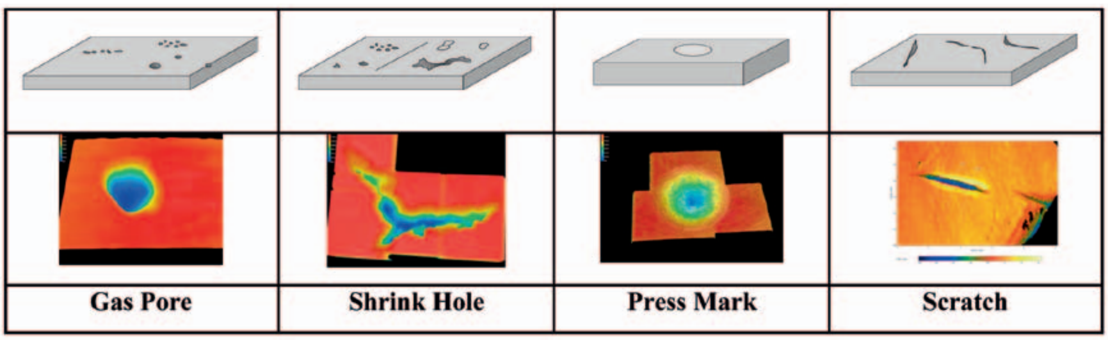

Fig. 1: *Examples of surface defects for basic description.*

High Resolution Metrology and Simulation

Influence of line edge roughness on scatter signatures for CD-metrology

B. Bilski, K. Frenner, W. Osten

Line Edge Roughness (LER) is a random deviation of a feature edge from its smooth, ideal shape.

It is stated that LER will become the most significant source of process control problems for features smaller than 50nm. This means that with every next lithography generation critical dimensions (CD) deviations are becoming its increasing fraction. Seen in this light, CD control will more and more converge to LER control.

In our previous research we determined that scatterometry can be used for LER metrology if we print the CD in a dense line-grating pattern and conduct two scatterometric measurements upon it, in two distinct setups, in which the plane of incidence of light used for the measurement is either perpendicular or parallel to the grating's lines, respectively [1]. After applying a realistic roughness to the edges of the given grating, the obtained results showed that the impact of the roughness can be quantified in terms of a so-called effective CD. However, due to the limitations of the applied simulation method (RCWA), the roughness was modeled using only one layer of staircase approximation.

In our recent study we used our in-house implementation of the Differential Method for solving the light-grating interaction problem. With its help we are free to create a complex model of a rough grating, with all the previously not included parameters, see Fig. 1. The creation of 2D roughness is an extension of modelling of 1D rough profiles. One only needs to start with a two-dimensional Power Spec-trum Density (PSD) resembling a low-pass filter. Such a roughness is much more close to realistic features.

In Fig. 2 we investigated the impact of side-wall angle and roundings in two cases: when the side-wall angle is 90° and the same when the side.wall angle is 85°. There are two interesting observations one can make. First and foremost we see a remarkable similarity between the 90° and 85° case. We observe that also the impact of roundings preserves the impact of LER.

Based on our investigations we conclude that the effective CD is valid in general case, with side-wall and top- and bottom-roundings. As a side-note, it is interesting to observe that the case when the two roundings exist simultaneously is a combination of cases when these roundings exist individually. This may support the statement that the more complex case could be composed of simple cases.

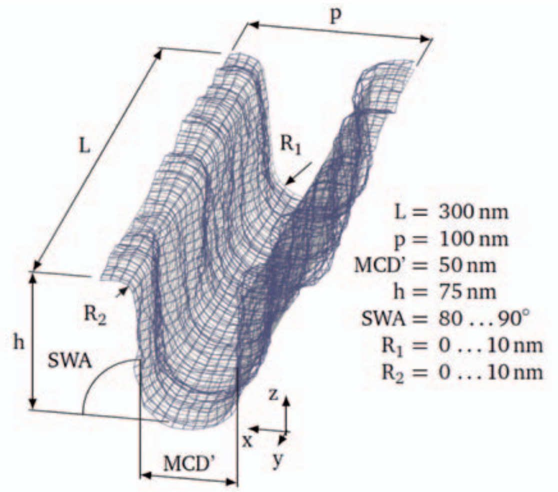

Fig. 1: *Modeling of a realistically rough line, now including side-wall angle and roundings.*

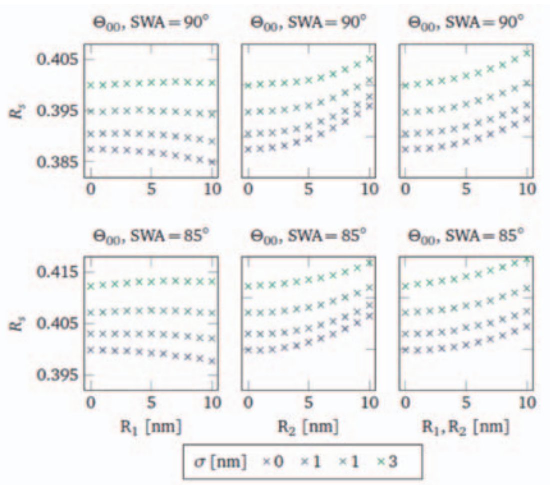

Fig. 2: *The impact of roundings and LER on reflectivity Rs.*

Supported by: European Community FP7
Grant agreement no. 215723

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Model-based reconstruction of periodic sub-wavelength structures by white light interference Fourier scatterometry

V. Ferreras Paz, S. Peterhänsel, K. Frenner, W. Osten

The white light interference Fourier scatterometry setup is based on a typical Fourier scatterometer. Instead of monochromatic illumination, the sample is illuminated using a broadband white light source. Additionally, a reference branch including a reference mirror for white light interference is introduced. The interfering pupil images from the object and reference branch are imaged with a Bertrand lens on a CCD camera. The schematic setup is depicted in Fig. 1. For reconstruction of the structure profile, a comparison between meas-ured and simulated pupil images for each z-position of the scanned reference mirror is performed until the best match is found.

As part of the DFG priority program SPP 1327 "Optically Generated sub-100-nm Structures for Biomedical and Technical Applications" we already presented in the ITO annual report 2009–2010 a simulation based analysis comparing the sensitivity of the white light Fourier scatterometry method to other scatterometric configurations. To verify the promising results obtained from simulation we now built up the experimental setup and compared the resulting structure reconstruction of a sub-lambda silicon line grating to measurements with an atomic force microscope (AFM) as well as with a scanning electron microscope (SEM).

The comparison between measured and simulated pupil images can be found in Fig. 2 Performing a library search the structure parameters can be reconstructed. The values obtained are compared to the AFM and SEM

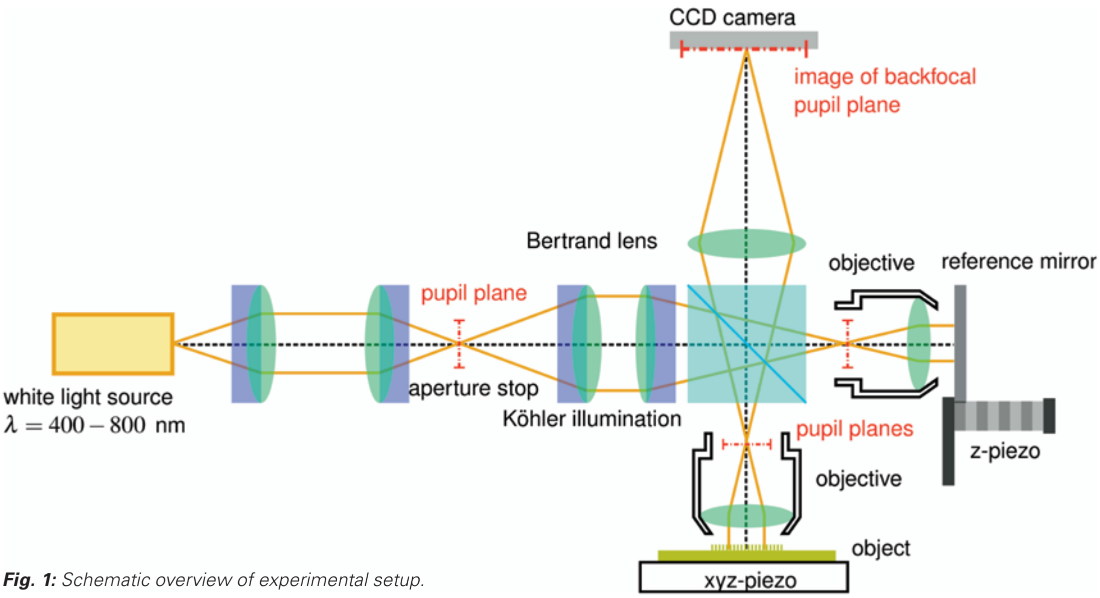

Fig. 1: *Schematic overview of experimental setup.*

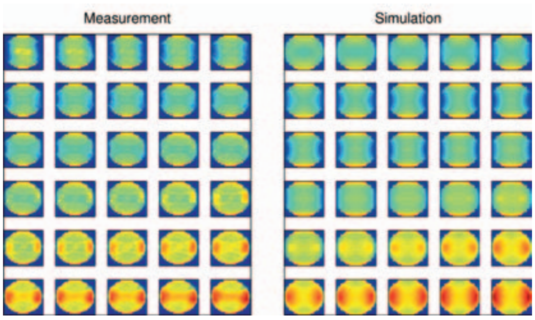

Fig. 2: *Measured and simulated pupil images for a z-scan of the reference mirror for the silicon grating CD=200 nm.*

reference measurements. The results can be found in Tab. 1. The reconstructed values are in good agreement, although the height is at the upper limit. One should keep in mind that scatterometry always integrates over the complete illuminated area (multiple periods of the line grating), while SEM and AFM always yield results at the chosen measurement site. Especially when the structure suffers from line edge roughness (LER), there can be differences in the values obtained by direct measurement methods compared with the integrated values obtained from our model-based measurement technique, which at the moment does not take into account LER effects.

The method is well suited for the model-based profile reconstruction (Fig. 3) of periodic line gratings of silicon, which are often used in the semiconductor industry. The measurements performed were reproduced satisfactorily by simulations. A library search inside the precomputed library identifies the best agreement and gives us the possibility to easily obtain the profile parameters of the analyzed structure.

Parameter	**Value [SEM]**	**Value [AFM]**	**Value [Reconstr.]**
Mid-CD [nm]	182 ± 7	–	182 nm
Pitch [nm]	400 ± 2	400 ± 2 nm	–
Height [nm]	76 ± 9	72 ± 7 nm	85 nm
SWA [°]	77 ± 3	–	77.5 °

Tab. 1: *Profile parameter ranges for the silicon grating (CD=200nm) measured with AFM, SEM and the reconstructed values obtained from the white light Fourier Scatterometry measurement.*

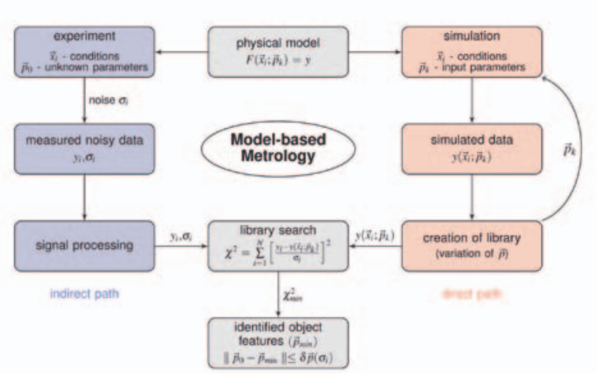

Fig. 3: *Schematic flowchart of the reconstruction strategy in general model-based metrology.*

Supported by: DFG (SPP 1327)
Project: "Optically Generated sub-100-nm Structures for Biomedical and Technical Applications" (http://www.spp1327.de)
Cooperation with: Nanotechnology Department at the Laser Zentrum Hannover e.V.

References:

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Design of microlenses using plasmonic stacks

L. Fu, K. Frenner, W. Osten

Plasmonics is a flourishing new field of science and technology due to its capability to confine light into a subwavelength volume, which induces strong light matter interactions at nanometer scales. Novel optical elements for light harvesting, plasmonic antennas, super-lenses and resonators have been developed in the last decade [1]. In the framework of a project with Bundesdruckerei GmbH, a novel type of plasmonic microlens using metal/dielectric stacks has been designed and simulated. The developed structure is of great importance for security elements, laser cavity reflectors or CD/DVD read/write heads with controlled focus size and length [2].

Fig. 1 shows a schematic of a periodic plasmonic structure embedded in polycarbonate (PC) with two unit cells. The metal is Silver and its dielectric constant is described by a Drude model. The dielectric is assumed to be PC having a refractive index of 1.58 at a wavelength of 630 nm. Our inhouse developed software package Microsim based on Rigorous Coupled Wave Analysis was used to simulate the structure. To obtain a parabolic phase front of the reflected beam, we treat the stacks as an effective medium and its effective index was approximated using the following equation, which is only valid when the thickness of the layers is much smaller than the wavelength:

$$\frac{1}{\varepsilon_{eff}} = \frac{h}{\varepsilon_d} + \frac{1-h}{\varepsilon_m}, \qquad (1)$$

in which, ε_m and ε_d is the permittivity of metal and dielectric, respectively, and h is the filling factor of the dielectric determined by $\frac{d_d}{d_d+d_m}$, in which $d_{(m,\,d)}$ is the corresponding thickness of the metal or dielectric.

The results of a plasmonic lens designed for 630 nm wavelength are shown in Fig. 2. To obtain a reflected focused field at z = -150 µm (the top surface of the structure locates at z = 0 µm), a parabolic wavefront of the reflected waves is desired. To achieve this, three pair of Ag/PC layers with thicknesses of 30/107 nm and widths of 25, 20, and 15 µm from bottom to top as shown in Fig. 1 were derived based on Eq.(1). Fig. 2(a) shows the intensity of the electric field above the stacks under the illumination of a p-polarized plane wave. It was also found that the focusing characteristics was kept under a tilted illumination of 30° and was robust in a larger wavelength and structure parameter range. Future work will focus on developing and fabricating plasmonic lens with a stronger focus capability and smaller size.

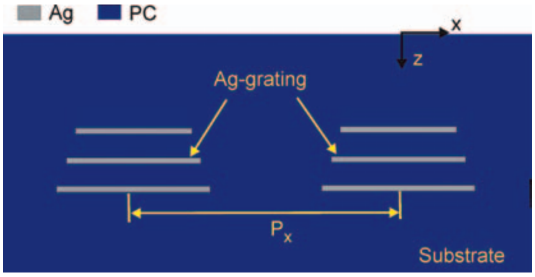
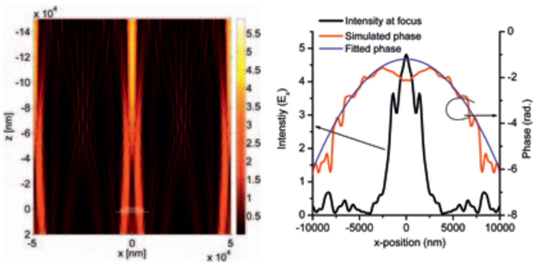


Fig. 1: *Plasmonic Ag/PC stacks as a microlens based on the effective medium theory. The metal is Ag described by a Drude model and the dielectric is Polycarbonate having a refractive index of 1.58 at 630 nm.*



(a) *(b)*

Fig. 2: *(a) Focus demonstration of three pairs of Ag/PC layers with thicknesses of 30/107 nm embedded in PC illuminated with a p-polarized plane wave at a wavelength of 630 nm. The width of the layers from bottom to top is 25, 20 and 15 µm, respectively. (b) Intensity distribution at z = -150 µm (the black curve), phase distribution (the red curve) at z = 0 µm, and the designed phase distribution using Eq.(1).*

This work was cooperated with Bundesdruckerei GmbH in the framework of the BMBF-Project UMABASA [3]. We thank the support from the Federal Ministry of Education and Research.

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[3] www.umabasa.de

Improved speckle simulator for rough surfaces using surface integral equations

L. Fu, K. Frenner, W. Osten

Any real surfaces, both those occurring naturally, and those fabricated artificially, are rough to some degree. It is of great interest and importance to know how this roughness affects physical properties of a surface. The scattering of electromagnetic waves from rough surfaces has been studied actively for more than a century now. More than thirty analytical approximation methods have been developed [1], among which the often used ones are small amplitude perturbation theory, Rayleigh-Rice and the Beckmann-Kirchhoff theory. In the last two decades, great advances in analytic approaches have been made by incorporating multiple scattering effects into the approaches. However, analytic models are all valid only in some specific application ranges [1].

In order to gain a fundamental understanding of how light interacts with a broad variety of rough surfaces, we aim to develop a rigorous numerical simulator for penetrable metals with a surface roughness in a large variation range. For this aim the full Maxwell equations have to be solved and surface integral equations with boundary element method were most often used. Based on Stratton-Chu's formulation and the associated boundary conditions on the tangential field components, a generalized formulation is obtained (PMCHW [2]):

$$\mathbf{E}^{\mathrm{inc}}(\mathbf{r})|_{\tan} = (L_1 + L_2)\mathbf{J}(\mathbf{r})|_{\tan} - (K_1 + K_2)\mathbf{M}(\mathbf{r})|_{\tan}\ , \quad (1)$$

$$\mathbf{H}^{\mathrm{inc}}(\mathbf{r})|_{\tan} = (K_1 + K_2)\mathbf{J}(\mathbf{r})|_{\tan} - \left(\frac{L_1}{\eta_1^2} + \frac{L_2}{\eta_2^2}\right)\mathbf{M}(\mathbf{r})|_{\tan}\ , \quad (2)$$

in which $\mathbf{M}$ and $\mathbf{J}$ are equivalent magnetic and electric surface currents induced by the incident fields $\mathbf{E}^{\mathrm{inc}}(\mathbf{r})$ and $\mathbf{H}^{\mathrm{inc}}(\mathbf{r})$, respectively. $\mathbf{K}_{(1,2)}$ and $\mathbf{L}_{(1,2)}$ are linear integrodifferential operators and η_1 and η_2 are the impedances of the two media above and below the surface.

To solve the two coupled equations, the rough surface, which is modeled using Monte Carlo methods, is discretized using isoparametric elements (boundary element method). In this work, the element takes a curvilinear quadrilateral shape as shown in Fig. 1, which is more accurate compared to planar elements [3]. The approximated field in each element is calculated through a linear combination of the 10 edges:

$$\mathbf{J}_{\tan} = \sum_{i=1}^{10} \boldsymbol{N}_i(\eta,\xi) S_{Hi}\ , \quad (1)$$

in which $\boldsymbol{N}_i = \boldsymbol{f}_i \boldsymbol{v}_i$ is vector element function along each edge, $\boldsymbol{v}_i$ is the gradient of η or ξ of the edge $\boldsymbol{i}$, and $\boldsymbol{S}_{Hi}$ denotes the line-integral of $\mathbf{J}$ along the edge $\boldsymbol{i}$ ($\boldsymbol{i}$ = 1, ..., 10) [3]. A similar equation exits for $\mathbf{M}$.

By using Galerkin method, the integration equations can be transformed into linear matrix equations. Once the unknown coefficients $\boldsymbol{f}_i$ for the effective current density in each element are solved, the $\mathbf{E}$ (or $\mathbf{H}$) field everywhere in space can be calculated correspondingly [2]. Especially, one of the advantages with this method is that both near and far field can be calculated accurately.

Fast multiple method combined with an iterative solver can accelerate the solution of the matrix equations.

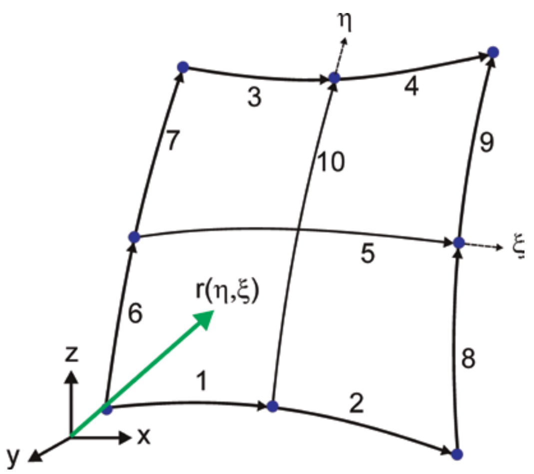

Fig. 1: *Numbering scheme of the edges of a curvilinear quadrilateral shape element.*

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Reconstruction of dynamical perturbations in optical systems

H. Gilbergs, K. Frenner

High-performance optics pose strict limitations on errors present in the system. External mechanical influences can induce structural vibrations in such a system, causing the optical components inside the objective to deviate from their designated positions. This can have an impact on the imaging performance, leading to blurred images or broadened structures in lithography processes.

A method to detect and predict the motion of the components of such an optical system by means of opto-mechanical simulation in combination inverse problem theory has been demonstrated. Such a method is the first step towards a control loop that corrects the lens positions with mechanical manipulators.

On the optical side of the simulation, raytracing is used for the generation of wavefront data of the system in its current state. A high speed Shack-Hartmann wavefront sensor is therefore implemented to gather the data needed for the reconstruction of the motion. The mechanical properties of the system are simulated using multibody dynamics, where the system is mod-elled as a set of rigid bodies (lenses, mounts, barrel), represented by rigid masses connected by springs that represent the coupling between the individual parts. External excitations cause the objective to vibrate. This motion can be represented by the eigenmodes and eigenfrequencies of the system.

The reconstruction of the system geometry as a function of time from the wavefront data is an inverse problem. Tikhonov regularization is used in the process in order to achieve accurate reconstruction results. This method relies on a certain amount of a-priori information on the system. The mechanical properties of the system are a great source of such information. It is taken into account by performing the calculation in the coordinate system spanned by the eigen-modes of the objective and using information on the spectrum of frequencies present in the current vibration as a-priori data. The positions of the individual lenses as a function of time is then reconstructed from several frames of the wavefront data and extrapolated to future timesteps in order to give a prediction on the system behaviour. This can be useful for applying and controlling countermeasures against the vibrations of the objective or for designing new systems that are less influenced by vibrations.

The results of this study have been published and presented in [1]. The next steps in this project are the extension of the reconstruction process to lens deformations and thermal expansion as well as experimental verification of the results.

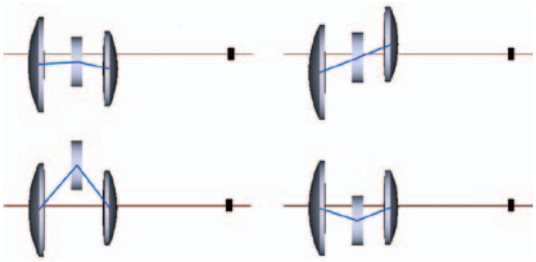

Fig. 1: *Visualization of the four eigenmodes used to represent system vibrations. The red line is the optical axis. The eigenmodes correspond to the eigenfrequencies* $f_1 = 0.70\ s^{-1}$ *(top left),* $f_2 = 1.10\ s^{-1}$ *(top right),* $f_3 = 2.07\ s^{-1}$ *(bottom left),* $f_4 = 4.11\ s^{-1}$ *(bottom right).*

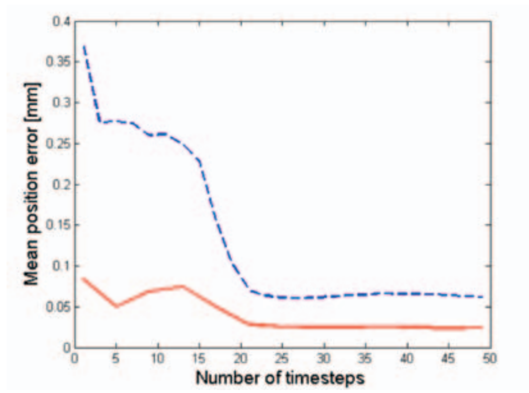

Fig. 2: *Comparison of the quality of the position prediction based on Tikhonov regularization (red) and least squares fit (dashed blue) vs. the number of evaluated timesteps. The results are improved greatly, especially for a lower number of evaluated timesteps. The smallest achievable mean position error is for the Tikhonov based method.*

Supported by: DFG (EXC 310/1) "Cluster of Excellence in Simulation Technology"

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Sub-wavelength imaging with metallic meander structures

P. Schau, L. Fu, K. Frenner, H. Schweizer. H. Giessen, W. Osten

In semiconductor manufacturing and nanotechnology, high-resolution metrology is crucial for process and quality control. At this point there are specialized tools available, which enable high-resolution imaging or metrology for individual process steps but no universal device. While demands of the industry have driven technology to the limits, none of the presented solutions is capable to image arbitrary sub-lambda structures directly in a contactless, fast and non-destructive way.

This is where the new research field of metamaterials comes into play. Metamaterials consist of periodic structures with dimensions smaller than the wavelength and can be designed to create particular electromagnetic responses that cannot be found in nature. Particularly interesting is the Veselago material, which exhibits a negative refractive index and can be used for superlensing as investigated by Pendry in 2000. Although a simple slab of silver already creates a perfect image of a sub-wavelength source, the image is still in the near-field and not magnified. Hence, all sub-wavelength information will still decay exponentially and vanish in the far field. Our research goal is to design a superlens capable of transforming evanescent waves to propagating modes, which then can be imaged via conventional microscopy (see below).

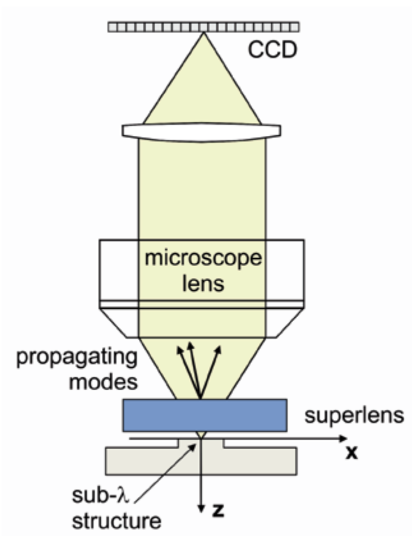

Fig. 1: *Basic setup for a superlens attached to a conventional microscope to enable sub-wavelength imaging.*

It has been shown that surface plasmon polaritons (SPPs) propagating on the metal/dielectric interfaces of a bulk negative index material (NIM) have a dominant influence on the unique properties of these materials. Consequently, one could replace bulk NIMs by resonantly coupled metallic surfaces that allow the propagation of SPPs.

A metallic meander structure (Fig. 2) is perfectly suited as such a resonant surface due to the tunability of the short range SPP (SRSPP) and long range SPP (LRSPP) frequencies by means of geometrical variation.

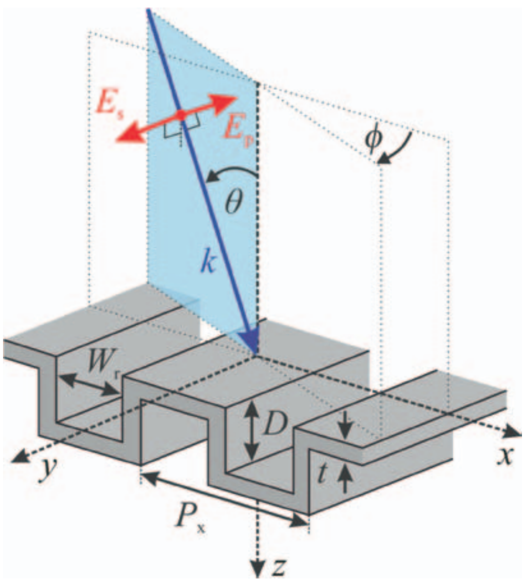

Fig. 2: *Meander structure, which enables near-field imaging similar to Pendry's perfect lens*

We have already demonstrated numerically how a stack consisting of two meander structures can mimic perfect imaging known from Pendry's lens. To observe sub-wavelength features in the far-field, however, we extended this principle towards a stack made up of meander structures with varying periodicities. A numerical simulation of this device is shown in Fig. 3.

In the course of the project, we have developed different ways to manufacture single and stacked meander structures preferably with e-beam lithography but also using other techniques such as interference lithography or focused ion beam milling. We have shown experimentally that the transmission spectra of these meander structures agree well with our numerical simulations. Furthermore, we demonstrated negative refraction occurring in meander structures using dispersion measurements and have high hopes to realize a proof of principle superlens in the near future.

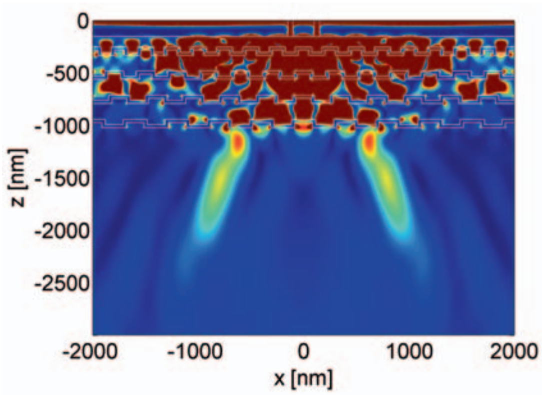

Fig. 3: *Stack consisting of four meander structures that magnifies two sub-wavelength holes by a factor of 8.*

Supported by: Baden-Württemberg Stiftung
Project: "Optical Metamaterials for process control environments (OPTIM)"
In cooperation with: 4th Physics Institute and Research Center SCoPE, Universität Stuttgart

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Polarization scrambling with plasmonic meander-type metamaterials for space applications

P. Schau, L. Fu, K. Frenner, H. Schweizer. H. Giessen, W. Osten

The polarization state of light is one of the most important properties for many optical applications. However, in some instances, such as earth observation from space, any exhibited polarization of the light is undesirable and depolarization of the light is critical for a good optical performance of a space-based instrument. One approach towards depolarizers are so called polarization scramblers or pseudodepolarizers, which divide the incident light beam into a large number of varying and intermixed polarization angles instead of truly depolarizing the light. Currently and historically, most pseudodepolarizers in space instruments utilize different arrangements of birefringent wedges. Major drawbacks of these designs are their bulkiness, heavy weight and limitation in size due to the anisotropy of the thermal expansion coefficient of birefringent materials.

Especially for space instruments, large-area and low-weight optical elements are desirable. So-called metamaterials could advantageously replace bulky standard optical components with thin layers of the same functionality but lower mass and volume. Depolarization effects in metamaterials have been discussed frequently in literature whereas metamaterial pseudodepolarizers have not been investigated yet.

The device proposed by ITO and the 4th Physics Institute is based on metallic meander structures (see OPTIM project report), which behave not only like an almost ideal linear polarizer, but also demonstrate a large phase retardation and polarization conversion capability between two orthogonal polarization states. The main idea of our approach consists of meander structures that are spatially distributed on a surface. Each meander structure within such a tile is rotated by a random angle (Fig. 1).

For perpendicularly incident light (θ = 0), we have described the behaviour of a single meander structure using Jones calculus. Because the meander structure itself is not depolarizing, it is valid to transform the Jones matrix to a Mueller matrix, which is dependent on the azimuth angle ϕ of the incident polarized light. The random orientation and distribution of the meander tiles effectively averages the azimuth angles and, hence, ϕ can be integrated from 0 to 2π. Then, within the pass band of the meander structure, the off-diagonal elements of the averaged Mueller matrix are zero and the diagonal elements around 0.5 or smaller. This makes the device already a good partial pseudodepolarizer.

To investigate the behaviour for oblique incidence, we used our in-house software tool Microsim to calculate the Mueller matrix rigorously. We found out that we can enhance the depolarization by stacking two meander sheets onto each other. With this scheme we achieve preliminary depolarization rates of >50% linearly polarized light and even 95% for circularly polarized light.

The presented polarization scrambler might be a good alternative to existing approaches and would be especially desirable for space applications due to its low weight and large-scale manufacturability using nano-imprint lithography.

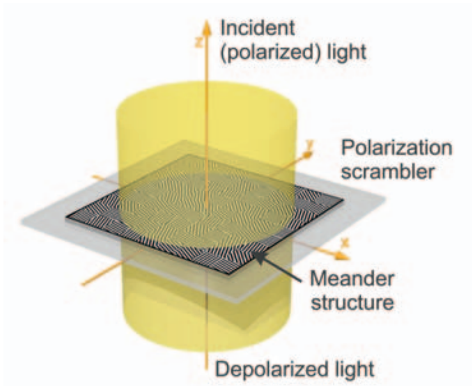

Fig. 1: *Working principle of the proposed polarization scrambler consisting of meander-type metamaterials.*

Supported by: ESTEC 4200022943/10/NL/AF
Project: "Metamaterials for Optical and Photonic Applications in Space"
In cooperation with: 4th Physics Institute and Research Center SCoPE, Universität Stuttgart; European Space Research and Technology Ctr., Noordwijk, Netherlands; cosine Research B.V., Leiden, Netherlands

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Depth-sensitive fluorescence measurements for diagnostic investigations

P. Schau, K. Frenner, W. Osten

Optical coherence tomography (OCT) is an important technology for non-invasive, in-vivo medical diagnostics. It enables the high-resolution recording of two-dimensional tomograms or three-dimensional volumes of biological tissue. Two mechanisms help separating the signal from the scattering background. First, reflected or backscattered light from outside the focal spot is suppressed by confocal discrimination. Additionally, the signal modulation is enhanced due to identical optical path lengths of both branches of the white light interferometry setup. Since the OCT relies on the interference between reference light and scattered light, this method cannot be readily extended for fluorescence measurements.

An alternative approach is the confocal fluorescence microscopy, which uses confocal microscopy to suppress the fluorescent light from outside the focal spot. Hence, only the fluorescent light in the focal plane, which is three to four magnitudes lower in intensity than the excitation light, is detected. However, the surrounding area is illuminated with full intensity, which might cause photobleaching. There are also other promising approaches such as the two-photon excitation microscopy or fluorescence lifetime microscopy.

However, for depth-sensitive fluorescence measurements of strongly-scattering samples such as biological tissue but also for technical surfaces, these methods are not well-suited. To enhance fluorescent depth-sensitive measurements, we cooperate with Institut für Lasertechnologien in der Medizin und Meßtechnik (ILM), Ulm and propose a combination of a structured white-light illumination and shearing interferometry (Fig. 1).

For this purpose, a structured illumination limits the area of interest on a rough scale. The exact lateral and axial position of the fluorescent molecules is then determined by a shearing interferometer. Using Fourier analysis, the curvature of the incident wave fronts can be calculated via the density and orientation of the interference fringes. Finally, the axial distance can be determined, which corresponds to the exact location of the particular molecule emitting fluorescence.

In a first step towards the realization of the whole system, we investigate and optimize the structured illumination. In a setup similar to a white-light interferometer, the light from the two branches is obliquely incident and interferes within the strongly scattering sample. Due to the short coherence length of the white light source, the light superposes only coherently for the exact same optical path length of both branches. Scattered or reflected light interferes only marginally or not at all. Hence, there is a 'plane' or 'sheet' within the strongly scattering sample that is illuminated with a higher intensity than the surrounding volume. The shape and intensity of the interferogram making up this plane can be manipulated with the bandwidth of the white light source and the angle of incidence, respectively. To what effect the scattering within the sample influences the measuring process will be investigated numerically by the ILM

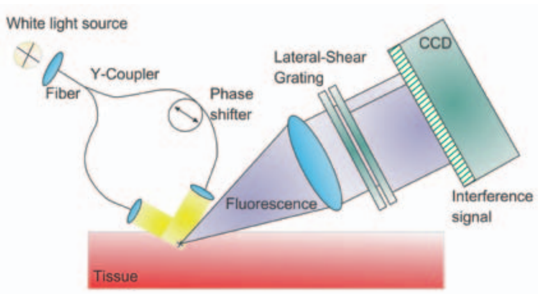

Fig. 1: *Principle setup of the measurement system consisting of the structured white-light illumination part and the shearing interferometer for detection of fluorescent light.*

Supported by: Baden-Württemberg Stiftung
Project: "Tiefenaufgelöste Fluoreszenzdetektion für die medizinische Diagnostik"
In cooperation with: Institut für Lasertechnologien in der Medizin und Meßtechnik (ILM), Ulm

Interferometry and Diffractive Optics

The Tilted Wave Interferometer (TWI): A quick and flexible approach to measure asphere and freeform surfaces

G. Baer, C. Pruß, J. Schindler, W. Osten

Producing precision optics is always connected to careful optical testing. With the need for better, smaller and lighter optical systems the use of aspheres and also freeform surfaces has become a necessity. New and improved fabrication technologies have been developed, and with them the need for adequate testing methods. Over the past decades the testing of aspheres and more recently also the testing of freeform surfaces has developed from the mere feasibility towards more economic solutions. This requires flexible solutions without expensive null optics such as computer generated holograms (CGH). Different scanning systems have been proposed that either test the surface under test point-wise or patch-wise. However, time sequential scanning leads to comparatively long measurement times. Our goal with the invention of the Tilted Wave Interferometer (TWI) was to reduce the measurement time to a minimum while still maintaining a high degree of flexibility [1].

The basic idea is to illuminate the surface under test (SUT) with a set of discrete wave fronts that are tilted with respect to each other. Thus, for any spot on the SUT there is a matching wave front that leads to an interpretable interferogramm patch. This allows in principle to capture the whole SUT in one measurement. For practical reasons – to avoid overlapping of the individual patches – only every second wave front in each direction is switched on. So in practice four measurements are taken of the SUT, with different wave fronts switched on (see figure 1). The SUT is not moved at all during measurement.

Fig. 1: *Synthetic phasemaps of the four measurement patch distributions when measuring a freeform surface.*

In the actual implementation, we can measure aspheres with gradient deviations of up to ±10° relative to the best fitting sphere in about half a minute's time. Since the tilting angles of the wavefronts cover angles of ±10° in both x and y-direction, the departure from the sphere does not need to be rotationally symmetric but can be an arbitrary freeform.

Fig. 2: *Free form surface (metal) with an astigmatism of about 800 µm.*

Figure 3 shows a measurement result of the freeform surface depicted in figure 2.

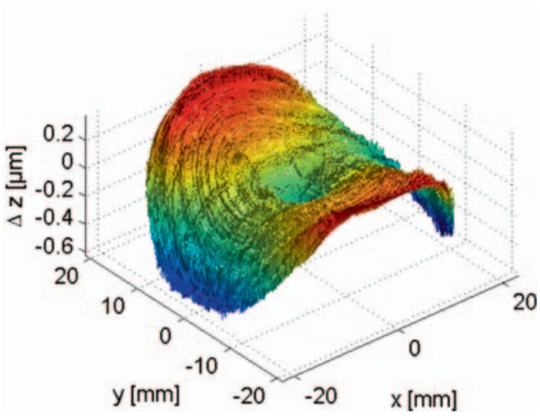

Fig. 3: *Measurement result showing fine tooling marks on the test surface.*

The measurement shows fine tooling marks on the aluminium surface, illustrating the high lateral resolution of the method.

As with all non-null testing methods a major topic is calibration. We use a system of polynomials to describe the aberrations of the interferometer. The coefficients of the system are optimized in the calibration procedure such that they can reproduce the results of a series of calibration measurements. The numerical properties of the polynomial system play an important role in the overall accuracy of the system and will be further investigated in current projects together with our partners from the PTB (Physikalisch-Technische Bundesanstalt).

As in all interferometric setups the positioning of the surface under test is important, since a) an incorrectly positioned surface might lead to vignetting and b) it adds alignment errors to the measurement. The TWI with its huge flexibility in terms of aspheric departure offers a unique situation for this problem. Even for a very badly positioned surface under test there will be a signal that helps finding the approximate correct position. Having reached this with a coarse alignment that can be automated (see last annual report) quite efficiently [2], the fine alignment could also be done automatically. However, this can be done virtually. We have realized an algorithm capable of estimating the correct position of the surface under test. With the position information, we can determine and subtract the alignment errors. As an example, figure 4 shows two measurement results of a surface under test that was laterally shifted by 20 µm between the two measurements. As can be seen, the algorithm obtains virtually the same measurement result.

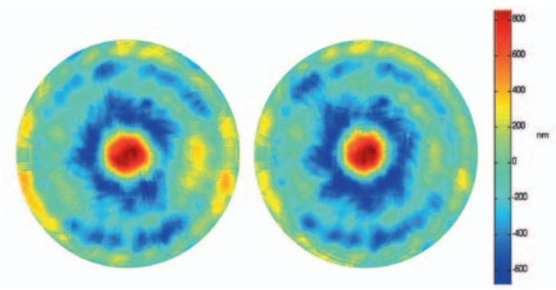

Fig. 4: *Two measurement results with surface under test shifted laterally by +-10 µm.*

The flexibility of the TWI approach is quite high, yet large surfaces beyond 100 mm diameter cannot be measured in one shot with our 4 inch interferometer. In the scope of the BMBF-project MesoFrei we currently investigating algorithms to extend the flexibility further with the help of stitching measurements and an automated setup that was developed by our industrial partner Mahr. In the stitching approach, the surface under test is measured patchwise and the results are stitched together to cover the whole surface.

We would like to thank the BMBF and the EU for funding parts of this work (projects MesoFrei, FKZN 13N10854 and EMRP JRP project IND10), the Baden-Württemberg Stiftung for financing part of this work in the project Nanofrom. The good cooperation with our project partners Mahr, PTB and IOF is greatly appreciated.

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Micro optical spatial polarization control

F. Schaal, C. Pruß, W. Osten

The scope of this project is the development of a compact micro optical device for non-pixelated spatial polarisation control.

The device (Fig. 1) is based on a photoaddressable material (PAM). The birefringence of the PAM is locally modulated due to the intensity of the addressing light. This enables the creation of non pixelated spatial polarization patterns with fewer artefacts compared to devices like spatial light modulators. The change in polarization depends on the polarization and intensity of the addressing light. The addressing is done with red light (655 nm), the usable wavelengths for polarization manipulation lies in the near infrared (NIR).

The micro optical addressing module (Fig. 2) uses VCSELs as light sources and diffractive optical elements (DOE) for beam shaping. Due to the small dimensions of the illumination system, several addressing channels can be realised in one device. By controlling the current through the VCSELs, different illumination patterns can be switched or combined.

The system can achieve resolutions up to 250 LP/mm and can induce a birefringence up to Δn 0.1. The switching time between two birefringence patterns is ~1.5 s.

Further work will focus on the enlargement of the addressable area, the integration of the system into a microscope objective, the realisation of a tuneable integrated phase contrast microscope and the combination with a plenoptic camera.

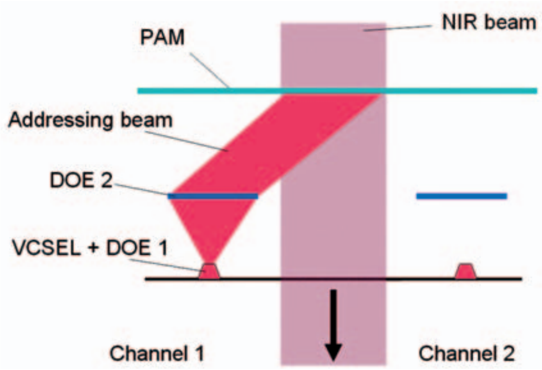

Fig. 1: *Schematic diagram of the basic setup.*

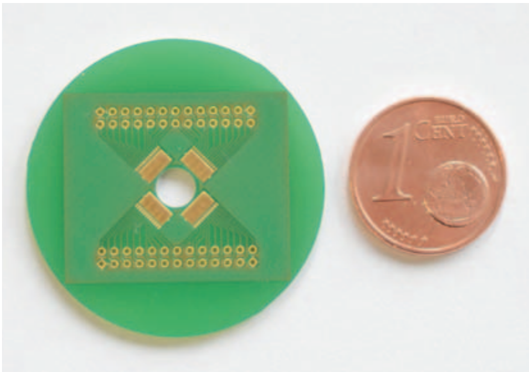

Fig. 2: *Micro-optical illumination unit.*

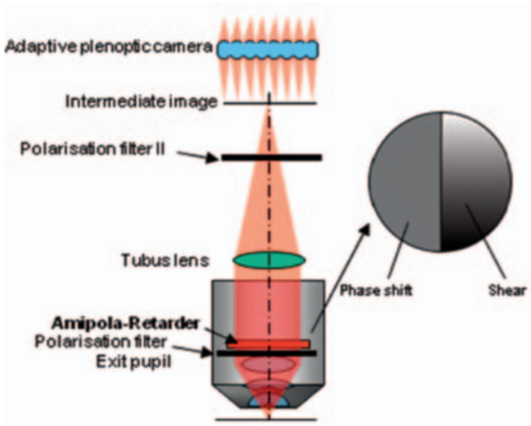

Fig. 3: *Microscope objective with adjustable phase contrast.*

Supported by: DFG OS111/35-1

This project is part of the DFG priority programme 1337 "active micro optics" and is done in collaboration with the IHFG (University Stuttgart), University Potsdam and others.

Fabrication of computer generated holograms on rotationally symmetric curved substrates

M. Häfner, C. Pruß, W. Osten

Hybrid optical elements that combine refractive and diffractive functionality are versatile components for all kinds of applications in imaging or metrology. In the past those elements were composed of a flat diffractive and a curved refractive surface. Fusing both functions in a single surface will enhance the capabilities of these optical components further. The fabrication of such precision elements is a challenge since most micro structuring tools are limited to flat surfaces. The growing interest in structuring non-flat surfaces arises in the increasing number of systems designed for this purpose [1,2]. At the ITO a powerful lithography scheme for the fabrication of high accuracy diffractive structures on rotationally symmetric curved substrates was established. The lithography tool was developed on the basis of the circular laser writing system CLWS300 [3] and allows for the fabrication of binary and grey scale structures on surfaces with slope angles of more than 15°.

Working with polar coordinates, the writing system is optimized for the fabrication of rotationally symmetric structures such as Fresnel Zone Plates. Positioning of the writing spot is realized by a rotating air bearing spindle that holds the substrate and a linear air bearing stage which addresses the radial coordinate on the substrate. Writing on curved surfaces implies that the writing head is able to follow the substrate topography. For this, we integrated a linear air bearing stage with small guiding errors and highly repeatable motion. The stage is mounted collinear to the angular axis, extending the polar coordinates to a cylinder coordinate system.

Figure 1 shows a schematic of the writing arrangement. Except for the rotating spindle all positioning is performed by linear stages. Tracking of the substrate topography is accomplished by continuously adjusting the height of the writing head according to the substrate surface sag, thus keeping the surface in the focal plane of the micro-scope objective. In order to account for fast autofocus response and wide range surface tracking, positioning of the focussing objective is realized by a hybrid approach combining a piezo actuator and a linear air bearing stage. Working in cylinder coordinates implies that the writing and autofocus beams are not perpendicular to the substrate surface when the substrate is curved. We therefore developed and integrated a novel auto focus approach that accounts for the challenge of focusing on tilted surfaces.

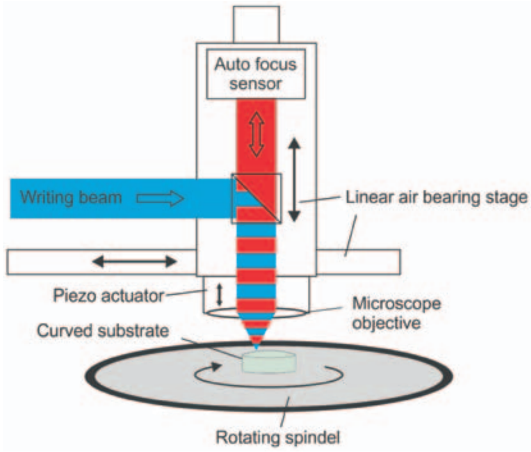

Fig. 1: *Schematic of the writing head.*

The writing system has proven to be capable of structuring rotational symmetric elements with surface slope angles of more than 15°.

Fig. 2: *Photograph of a reflective Fresnel zone plate written on a spherical lens.*

Figure 2 shows the photograph of a reflective Fresnel zone plate written on the spherical surface of a lens. The surface topography at the outer edge of the structured area can be seen in figure 3.

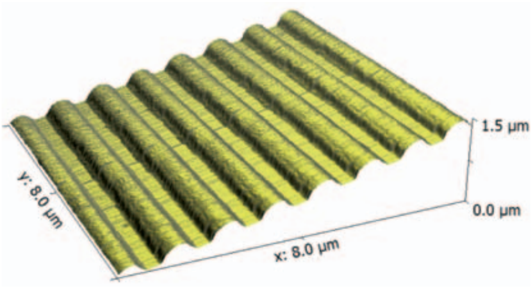

Fig. 3: *AFM-Scan of a binary structure at a surface angle of 18.6° (surface tilt partially removed).*

The AFM-scan shows a structure period of 0.95 µm and a surface angle of approx. 18.6°. Furthermore we fabricated continuous grey scale structures with a period of 5 µm and a depth of approx. 1 µm at surface angles of up to 15°. An AFM-Scan of that structure can be seen in figure 4.

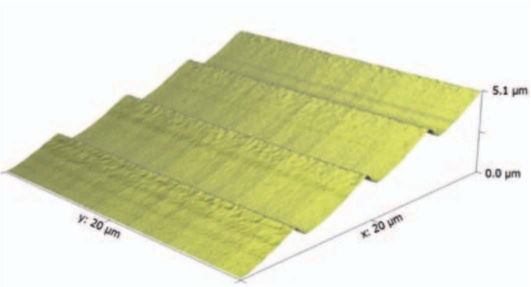

Fig. 4: *AFM-Scan of a grey scale structure at a surface angle of 15° (surface tilt partially removed).*

The writing system has been designed to allow for future extension i.e. the fabrication of off-axis diffractive structures or the combination with advanced writing techniques for the fabrication of high frequency structures [4].

Supported by: BMBF FZK 16SV2309
Project: "Lynkeus", in cooperation with: ZESS University Siegen, PMD Technologies GmbH, U-L-M photonics GmbH, ifm electronic GmbH, University Heidelberg (IWR).

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Cost effective production of diffractive multi-level elements

F. Schaal, C. Pruß, W. Osten

Diffractive optical elements have numerous applications for e.g. beamshaping, chromatic correction or optical measurement systems. But due to the high costs of diffractive elements their application is limited to high volume markets or special purposes.

For applications with small and medium number of pieces the costs of the elements and the replication have to be lowered.

Injection-compression as used in the production of CD/DVD is a fast and mature method for the replication of microstructures and can be utilized for the cost-effective replication of diffractive elements (Fig. 1).

We investigate the fabrication of masters for the replication process by gray scale lithography and laser direct writing in photoresist. The process and the materials must be compatible with production tools for optical data storage discs. This includes the use of special machine mountable substrates and compatibility of the resist to the fabrication of metal masters.

Laser direct writing can cause roundings, height fluctuations depending on the surrounding structures and structure size. Therefore this must be corrected by proximity correction of the writing data to fabricate multi level elements without costly and time consuming experimental iterations.

The proximity correction needs to take the measured beam profile of the writing spot, the nonlinear gray scale properties of the photoresist, sampling of the structures due to the circular writing and stray light into account.

The inclusion of these effects into the writing data leads to structures with less artefacts and generates precise and more efficient diffractive optical elements (Fig. 2).

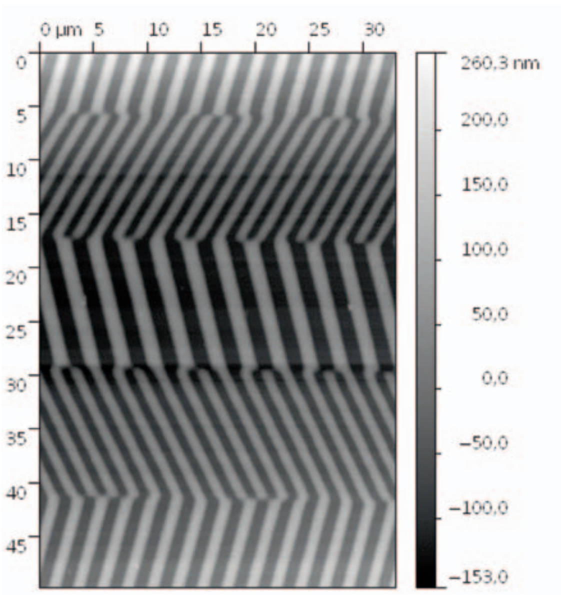

Fig. 1: *Diffractive rotary encoder structure replicated by injection-compression.*

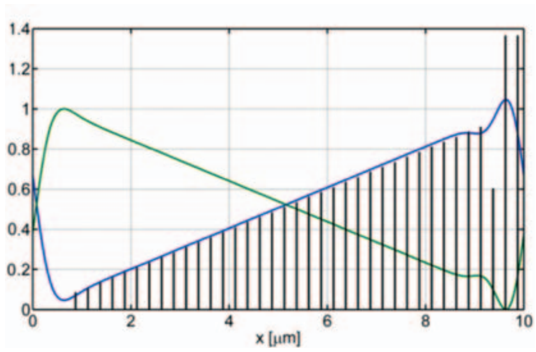

Fig. 2: *Optimized illumination pattern for increasing the diffraction efficiency of blazed gratings (increase of 5% diffraction efficiency).*

Supported by: BMBI (FKZ KF2281402AB2)
Project: "Kosteneffiziente Grautonlithografie für diffraktive Multi-Level Elemente"
Partner: Holoeye Photonics AG

Fabrication of diffractive and micro-optical elements for external partners

F. Schaal, C. Pruß, W. Osten

One of the major issues that prevented the wide use of diffractive elements in optical systems is still the availability of these high precision optical elements. At the institute we maintain a long tradition of design and fabrication of diffractive optical elements – our first writing system was installed in the 70s. In 1995 we started to produce high precision diffractive optical elements (DOE) in a laser direct writing process and have continuously developed our laser writing capabilities since then, including gray scale lithography, scanning interference lithography, writing on curved substrates.

Our fabrication capabilities are available for external partners.

Core of our microstructure fabrication are two circular laser writing systems, flexible high precision tools that work in polar coordinates, comparable to a DVD writer. This working principle offers the advantage of a high, continuous scanning speed and facilitated fabrication of rotationally symmetric structures. One of the systems is also capable to write on rotation symmetric curved substrates e.g. lens surfaces.

The writing is not limited to circles but allows writing arbitrary structures such as linear gratings or microlenses. Refractive microstructures and blazed gratings are written in grayscale mode where the writing beam intensity is varied with at the moment up to 256 levels.

The substrate size can vary from a few millimeters to 300 mm in diameter. The shape can be rectangular, round or any other reasonable outline. The system allows substrate thicknesses up to 25 mm.

The structures are written directly into photoresist. The resulting photoresist profile is then either used directly (e.g. for mastering) or is transferred into the fused silica substrate using dry etching (ICP).

Example applications that we have designed and developed with academic and industrial partners are:

- CGH for aspheric testing
- Custom made diffractive and refractive microlens arrays
- Beam shaping elements
- DOE for optical sensors
- DOE for imaging systems
- Custom phase structures
- Phase contrast plates
- Nipkow microlens disks
- Master fabrication for mass replication
- Writing on curved substrates e.g. for chromatic correction of optical systems

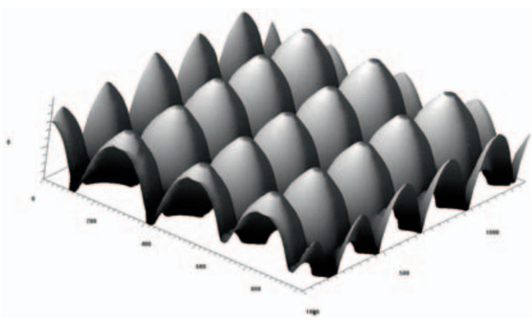

Fig. 1: *Aspheric refractive micro lens array.*

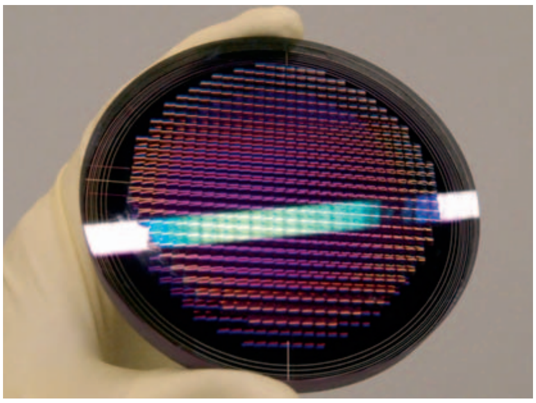

Fig. 2: *Double sided diffractive micro lens array with individually optimized lenses.*

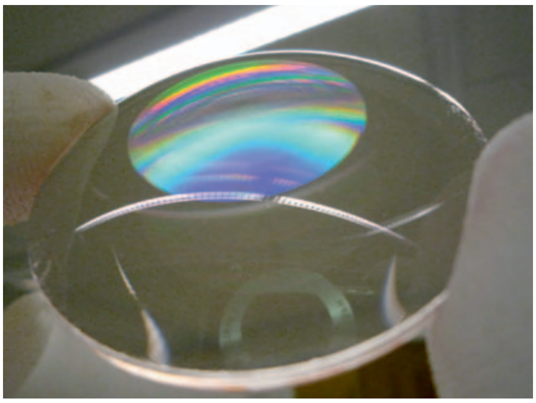

Fig. 3: *DOE on a lens surface.*

Phase errors introduced in CGH by rigorous effects

S. Peterhänsel, C. Pruß, W. Osten

The German part of the trilateral DFG-project "Inverse source and inverse diffraction problems in photonics" deals with the detection of phase errors in CGH's introduced by rigorous effects.

A common test for aspheres and freeform surfaces is the null test. Here a CGH is introduced in the object path of an interferometer to generate a phase front that matches the surface under test. As the line densities of the CGH are becoming higher, it is no longer sufficient to use scalar approximation [1, 2]. This changes also the influence of fabrication errors onto the reconstructed phase [3].

For a comparison the reconstructed phase of a binary grating in reflection was calculated with scalar approximation and rigorous simulation. The period of the grating was decreased from 6 to 1 µm, see figure. For grating periods smaller than 2.8 µm or 4.5 λ the phase difference is larger than λ/100.

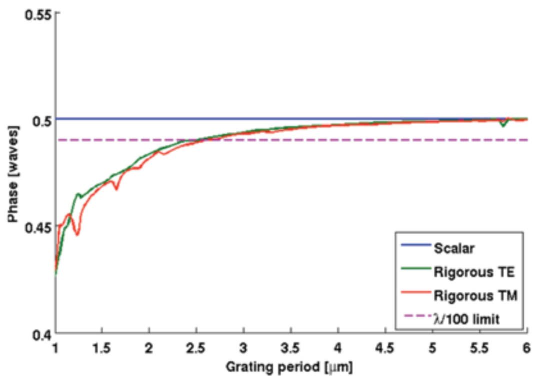

Fig. 1: *Comparison of scalar approximation and rigorous simulation for a binary grating with DC of 0.5 and variable grating period.*

The influence of fabrication tolerances was studied for different gratings (binary, multi level, blazed) with periods of 1µm. Therefore the phase difference between the desired grating and a grating with a variation of 1 % in one parameter was analysed. To determine which effects can still be described by scalar approximation the scalar phase difference for the same parameter variation was subtracted.

$$\Delta\phi = \Delta\phi_{\text{rigorous}} - \Delta\phi_{\text{scalar}}$$

The studied grating parameters were duty cycle, height and side wall angle. In addition the influence of polarisation and angle of incidence were evaluated and showed a significant phase change, see figure.

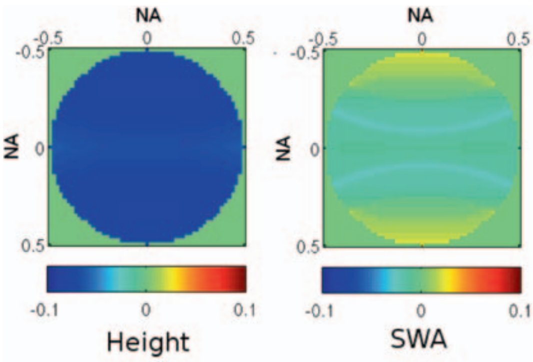

Fig. 2: *Phase errors for binary gratings with variations of 1%, 1. order, TM polarised light and incidence angles of ± 0.5 NA.*

Future work will focus on solving the inverse problem between generated phase and measurable quantities.

Supported by: DFG (OS111/32-1)
Project: "Inverse source and inverse diffraction problems in photonics "
Partners: University of Joensuu, Finland and Tsinghua University, China

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Coherent Metrology

Optical methods for assessment of transport and age induced damages on artworks

M. Morawitz, I. Alexeenko, M. Wilke, G.Pedrini, W.Osten

Cultural heritage plays a significant role in the development of a society. Therefore, it is of great interest to make works of art accessible to the general public. The subsequent increase of museum loan services increases the risk of accelerated degeneration. Hence, in addition to the age related deterioration, transportation can be another source of damage. Despite modern packaging technologies, smallest vibrations and environmental climate change can add up and damage the transported object. In order to preserve and restore our cultural heritage it is necessary to detect damages at an early stage before they reach a critical extend. Optical structural diagnosis techniques like shearography can provide the necessary means to identify those defects [1].

Shearography is a coherent-optical measuring technique sensitive to the gradient of deformation. In order to detect structural defects the object is illuminated by an expanded laser beam (see Fig. 1). The optically rough surface scatters the incident light forming a speckle pattern, which is imaged through a Michelson interferometer by a CCD camera. One mirror of the interferometer is slightly tilted producing a pair of laterally sheared images. An infrared lamp is used to thermally load the object under investigation. Sheared speckle interferograms before and after thermal loading are processed to obtain shearograms. The fringe pattern of a shearogram describes a relative difference in the phase, which is related to the derivative of deformation and therefore to inner stress caused by structural defects.

Recently the Stuppach Madonna (painted 1514–1516), a painting by Matthias Grüne–wald, was investigated with shearography (see Fig. 2) after the return from the exhibition "Himmlischer Glanz. Raffael, Dürer und Grünewald malen die Madonna" in Dresden, Germany. In addition to the necessary process of restoration the condition of the panel painting should be evaluated and recorded where shearography was applied to assist the conservators. Due to the size (186 cm × 150 cm) the painting was segmented into 16 subareas. For each subarea a separate shearographic measurement was conducted. The shearograms revealed a variety of defects like bubbles, delaminations and tunnels caused by wood worms. Even the planking of the wooden panel and putty could be observed. [2]

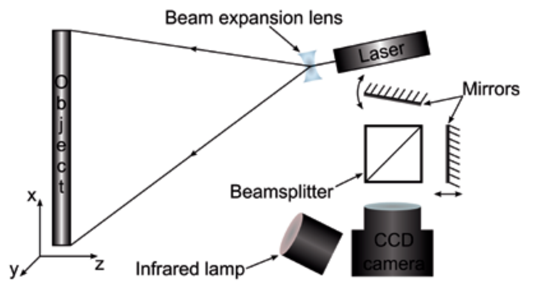

Fig. 1: *Shearography setup. The object under test is illuminated by an expanded laser beam. The resulting speckle pattern is imaged through a Michelson interferometer with a CCD camera before and after thermal loading the object with an infrared lamp.*

Fig. 2: *Stuppach Madonna before restoration. The shearograms show different kinds of defects like bubbles, delaminations (red) and tunnels caused by wood worms (blue). Some features of the painting like the planking (yellow) and putty (green) are also observable.*

Supported by: DFG (OS 111/34-1)
Project: „Die materielle Veränderung von Kunst durch Transporte"
In cooperation with: Staatliche Akademie der Bildenden Künste Stuttgart

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High resolution 3D microscopy using opposed-view dark-field digital holography

A. Faridian, G. Pedrini, W. Osten

The aim of this DFG project is to develop a label-free three-dimensional microscopy system to enhance the spatio-temporal resolution and the contrast in imaging of complex biological samples. The lateral resolving power of an optical system is diffraction-limited according to Abbe Criterion. Considering the fact that complex specimens consist of different materials in various layers, there are some practical obstacles that prevent achieving the theoretical resolution, e.g. the diffraction patterns coming from the upper layers. Here, we are developing a coherent microscopy method to overcome this limitation using an opposed-view approach.

In the setup, four off-axis digital holographic microscopes (DHM) have been combined in one configuration to record digital holograms in two illumination modes (dark-field and bright-field), from two opposing views of the sample. Two different wavelengths were used to be able to separate the dark-field and bright-field signals for each imaging view. The wavelength selection depends on the absorption/transmission coefficient and scattering property of materials inside the sample. To perform dark-field imaging, we used a wavelength in the low frequency spectrum of the visible window, in which biological samples have higher scattering rate. A single mode laser diode, operating at 660 nm, was used as a light source for this imaging mode. For the bright-field imaging mode, the wavelength of 405 nm was utilized. This wavelength is in the high frequency region of the visible spectrum that provides with a higher resolution and also a higher contrast due to the relatively higher absorption coefficient of the biological tissue.

Figure 1 shows the schematic diagram and a photo of the actual setup in the laboratory. A pair of Nikon dark/bright-field objectives, with the magnification of 20x and NA=0.45, has been implemented in the setup. Each objective creates a hollow light cone to produce dark-field illumination and is designed in a way to be capable of simultaneously imaging with dark-field and bright-field illumination in both transmission and reflection modes. Two CCD cameras have been installed in each view; one to collect the dark-field and the other to collect the bright-field signal. The entire dark-field signal is directed to the corresponding CCDs using the dichroic mirrors installed in the imaging path (DM1 and DM2). The bright-field signal is transmitted through the dichroic mirrors and guided to the corresponding CCDs by the beam-splitters BS1 and BS2.

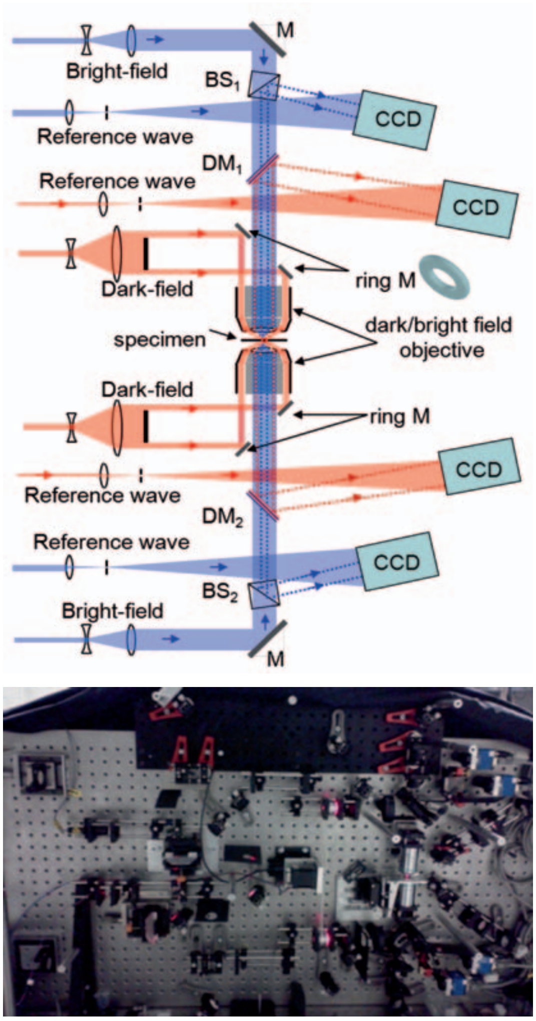

Fig. 1: *Top: Schematic diagram of the imaging part of the opposed-view DHM setup, showing both dark-field and bright-field configuration. Bottom: the arranged actual setup in the laboratory.*

We took the larvae of sea urchin (about 24 hours old) for our investigations. Figure 2 shows the digitally reconstructed images of a larva taken by the top view (left column) and also the bottom view (right column) DHM.

In this example, the larva was kept floating in a water. The reconstructed images which are shown in Fig. a1) and b1) correspond to a specific larva taken from the top and bottom view, respectively. Figures c1) and d1) show the corresponding phase for each view. Figures a2) and b2) represents the reconstructed images of another neighbouring larva in the same medium and c2), d2) represents the corresponding phase. Comparing (a) and (b), one can see the difference in the structures from different imaging views for a given focused image plane.

For this sample, a clean water environment containing only a few larvae has been prepared; otherwise the presence of the other particles in the upper (or lower) layers could reduce the image quality from a given imaging view by creating some diffraction patterns. However, the opposed view system is also intended to improve the image quality it in this case.

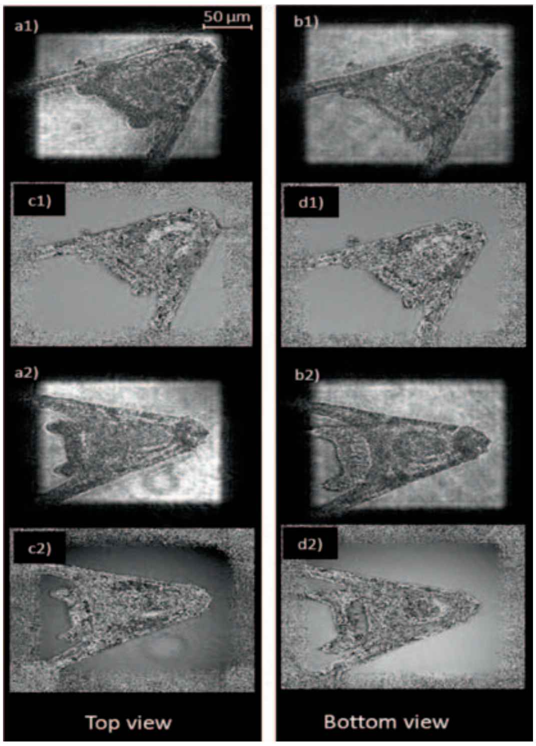

Fig. 2: *Left column: reconstructed intensity (a1, a2) and phase (c1, c2) images of two sea urchin larvae, floating in a water medium, taken from the top view. Right column: reconstructed intensity (b1, b2) and phase (d1, d2) images of two sea urchin larvae, floating in a water medium, taken from the bottom view.*

To present the dark-field part of the setup, only the result of the bottom view is reported here. To be able to better evaluate the dark-field result, a bright-field image of a larva, taken by a 405 nm laser diode, is presented in figure 3.a). A dark-field image of the larva, taken by a 660 nm laser diode, is shown in figure 3.b). Being based on scattering, speckle field noise is inevitable in coherent dark-field microscopy (figure 3.b). Therefore, to supress the speckle noise, we illuminated the sample with various speckle fields and derived the final image by averaging over the fields. Figures c-d) represents two different focuses of dark-field image of the larva after averaging over 100 speckle field illuminations. Figures 3b) and 3d) are in the same focusing position.

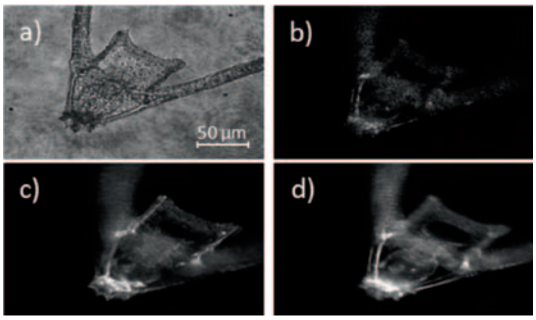

Fig. 3: *a) Bright-field image of a larva taken using a 405 nm laser diode, b) dark-field image of the larva illuminated by a speckle field of a 660 nm laser diode, c-d) two different focuses of dark-field image of the same larva after averaging over 100 speckle field illuminations.*

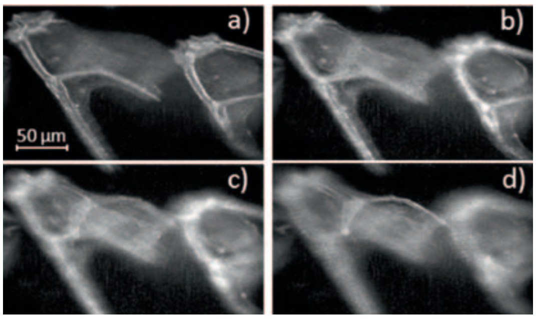

Fig. 4: *Reconstructed intensity image of two larvae averaged over 100 speckle fields, figures (a-d) shows sequential digital focusing for different layers of the larvae.*

Therefore, the holograms are also recorded using different speckle field illuminations. Figure 4 represents different focuses of the reconstructed intensity images of two larvae, averaged over 100 holograms, which were recorded sequentially using a Labview program in about 10 seconds; the process can be even much faster utilizing a high speed Camera.

Compared to the bright-field image, the skeleton of the larvae is visible with more contrast and the sharp focus plane is easier to find for a specific region of interest. Also, some internal structures of the body, which have more scattering rate, are more recognizable in the dark-field images.

Supported by: DFG (OS 111/32-1)
Project: "High resolution 3D microscopy using opposed-view dark-field digital holography"

References:

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3D UV holographic microscope for biomedical imaging

A. K. Singh, A. Faridian, G. Pedrini, W. Osten

Digital holographic microscopy (DHM) is a combination of holography and microscopy and has the ability to extract essential 3D information from a single recording. With the help of numerical reconstruction and digital focusing DHM has become a new tool for biomedical imaging.

Like in conventional microscopy, in DHM the diffraction-limited lateral resolution, introduced by the Abbe's criterion (λ / NA), can be increased either by increasing the NA of the optical system or by using shorter wavelengths.

The main purpose of our investigations is to increase the resolution and the contrast for the imaging of live cells. For this purpose we built an off-axis DHM set-up using high NA objective (0.75) and UV light sources in the range of 193 nm to 355 nm. To avoid stray reflections and aberrations least possible optical components are used.

In the beginning we used a laser source having wavelength 193 nm and we could achieve a lateral resolution of 250 nm however this kind of light is almost fully absorbed by living cells and thus essential informations are lost. Figure 1 shows the reconstructed amplitude (a) and the phase (b) of HeLa cells which were recorded with the 193 nm wavelength light source. The current investigations are focused on longer wavelengths. We used 355 nm for imaging but the absorbance of live cells at this wavelength is 10-15 % and thus the cells are nearly transparent and the contrast of the images is very poor. Figure 2 shows the images of reconstructed amplitude (a) and the calculated phase (b).

Currently we are using 266 nm light source. The absorbance at this wavelength is more than 50 % and live cells are semi-transparent to this wavelength, creating an ideal condition for high contrast imaging. Figure 3 shows the high contrast and resolution images of live cells at 266 nm. Figure 3 (a), (b) and (c) show the reconstructed amplitude, the calculated phase map and 3D image of the HeLa cell.

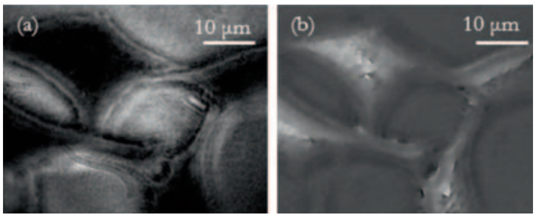

Fig. 1: *Imaging of Hela cell using 193 nm wavelength light source (a) reconstructed amplitude and (b) Phase map.*

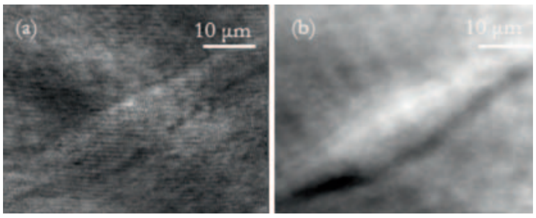

Fig. 2: *HeLa cell imaging using 355 nm wavelength light source (a) reconstructed amplitude (b) calculated phase map.*

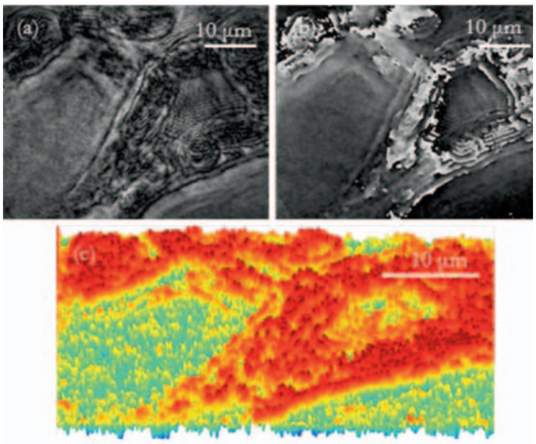

Fig. 3: *(a) reconstructed amplitude (b) phase map and (c) 3D image of HeLa cell with 266 nm wavelength light source.*

Supported by: DFG (OS111/19-3)
Project: "Digitale Holographie mit adaptiver Wellenfrontformung zur hochauflösenden Untersuchung von 3D-Mikrostrukturen im tiefen UV-Bereich"

References:

[1] Faridian, A.; Hopp, D.; Pedrini, G.; Eigenthaler, U.; Hirscher, M.; Osten, W. "Nanoscale imaging using deep ultraviolet digital holographic microscopy", Opt. Exp, 18, 14159:14164, 2010.

Knowledge management in virtual labs and remote experiments

M. Wilke, M. Riedel, G. Situ, I. Alekseenko, G. Pedrini, W. Osten

The MWK-funded project BW-eLabs focuses on the development of a collaboration infrastructure for scientist, providing access to remote laboratories, data bases for results (stored as raw data with added meta data) and publication of experimental results. The ITO contributes a remote experiment for holographic microscopic metrology. The experimental setup of the digital holographic microscopic system is shown in Fig 1.

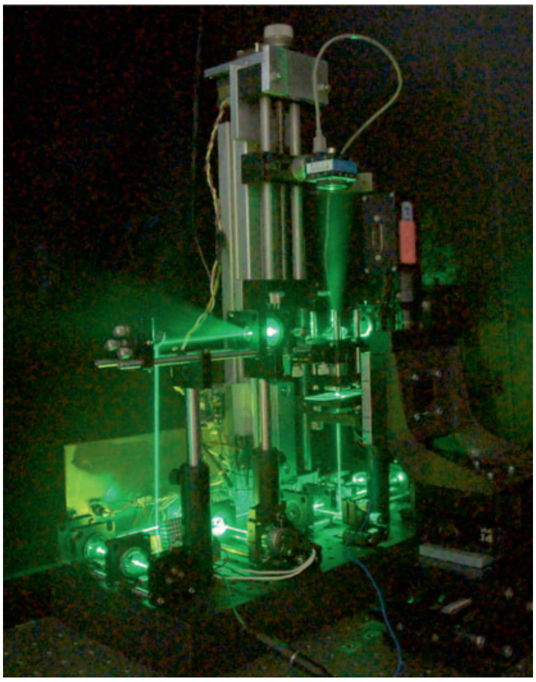

Fig. 1: *Experimental setup of the holographic microscope.*

A Nd-YAG Laser is coupled into a fiber, which guides the beam into a coupler that subsequently divides the input laser beam into a reference arm and object arm. The object arm fiber can be switched for different illumination modes, i.e., transmission mode or reflection mode, depending on the property of the object to be investigated. The object is imaged through a 20x/0.5 microscopic objective. The reference fiber is coupled into the system using a beam splitter as shown in Fig. 1, to interfere the reference beam with the object wave. The microscopic table is mounted on an electric-driven 3D positioner, allowing the user to shift the field of view at sub-micron precision. The object is imaged using a 20x/0.5 microscopic objective and a CCD camera is used to record the hologram. The camera has a large sensing area, and a high numerical aperture can be obtained when it is placed close to the object, even in a lenseless configuration. The hologram is transferred to the computer for subsequent processing, including numeric reconstruction of phase and intensity and the calculation of phase difference compared to previous holograms.

The data and control flow of the remote experiment are shown in Fig. 2. The experiment is controlled through LabView, with remote control provided by remote desktop system (VNC), connecting through a proxy

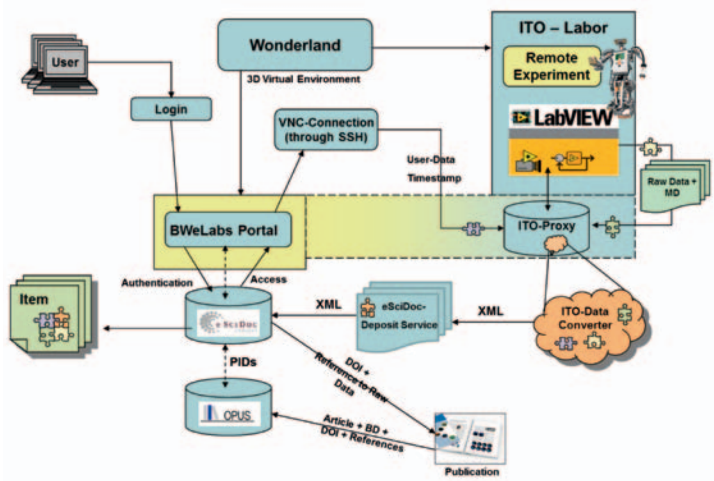

Fig. 2: *Data and Control Flow in BW-eLabs*

using an encrypted channel (SSH tunnel), adding standard authentication through the modular authentication system PAM and encryption for security, based on existing software such as Java-Portlets running on the BW-eLabs Portal server and Python modules on the proxy server.

The connection to the data base and publication backend eSciDoc is work in progress and will allow automatic storage and access to experimental results, including identification through a unique, persistent digital identifier (DOI). eSciDoc is connected to the OPUS document server at the University of Stuttgart for publication. Sets of actual experimental data can be accessed and referenced through OPUS, using the DOI identifiers.

In addition to the generic access using VNC, a 3D virtual environment (Wonderland) is being implemented. This frontend is intended to provide intuitive access to the hardware, as well as support collaboration between users by providing communication channels.

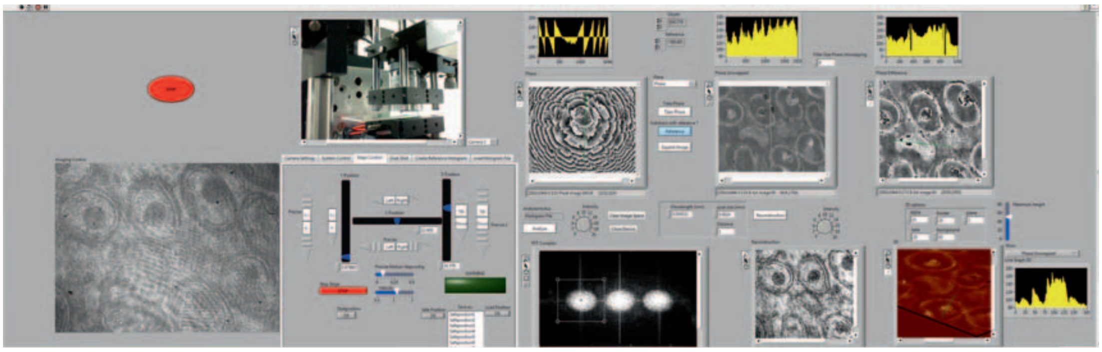

Fig. 3: *User Interface*

Supported by: Ministerium für Wissenschaft, Forschung und Kunst Baden-Wuerttemberg (MWK)
Project: „BW-eLAB"
Partners: RUS, UB (University of Stuttgart); FMF, Rechenzentrum (University of Freiburg); FIZ Karlsruhe; Stuttgart Media University

References:

[1] Wilke, M. ; Alekseenko, I. ; Situ, G. ; Sarker, K.; Riedel, M. ; Pedrini, G.; Osten, W. „Remote laboratory for digital holographic metrology", Proc. SPIE 8082, Optical Measurement Systems for Industrial Inspection VII, 80820D (May 26, 2011).

Compression of digital holograms

M. Wilke, G. Pedrini

This project investigates the application of data compression techniques to digital holography. Advances in computational power and the decreasing pixel pitch of high-end cameras are moving real-time capable, digital holography into the realm of near future feasibility. Physical limitations impose large detectors with small pixels, resulting in very large images (typically 12 Mega-Pixels at 10 bit depth). Holographic video has been proposed. These large sets of data suggest the use of compression techniques to reduce the storage size or transmission bandwidth required. However, while they are recorded on the same hardware (CCD or CMOS detectors) as natural images, holograms differ significantly from these. Holograms store information about both the amplitude, as in a normal image, and the phase in interference fringes. This difference requires a reevaluation of the standard compression techniques before they can be applied to holograms.

The holograms used in this investigation are Phase Shifting (PSI) holograms. It has been shown, that a JPEG2000 style compression scheme works best in the plane of reconstruction. To account for this, the algorithm being developed in this project applies a Fresnel transformation and separates the phase and amplitude for independent processing.

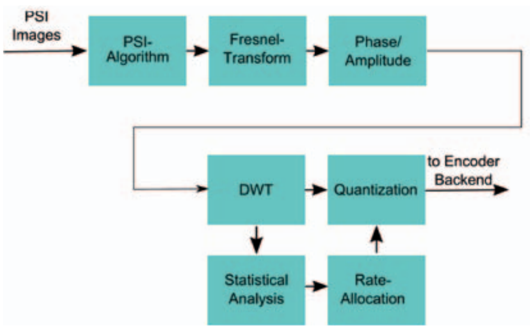

Fig. 1: *Encoding Process*

The results of the statistical analysis have shown that the statistics of the wavelet coefficients for the amplitude of the reconstructed wavefront in the object plane show a distinct two-component behavior. One component, with the coefficient distributed Gaussian, represents the speckle field, while the other, with an approximately Laplacian distribution, correspond to the macroscopic shape of the object.

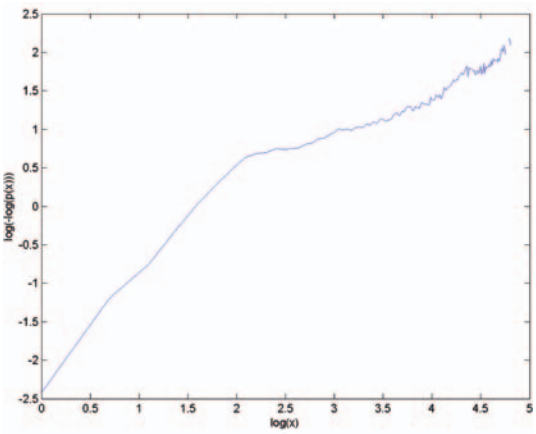

Fig. 2: *Histogram of the intensity wavelet coefficients in logarithmic scale*

The wavelet coefficients for the phase are Gaussian distributed, although the distribution is very noisy. This noise is the result of numerical instabilities in calculating the phase for amplitudes close to zero. We have shown that the noise can be suppressed using a mask based on the amplitude of the wavefront. These results indicate, that standard compression algorithms can be applied successfully to Fresnel propagated and wavelet analyzed PSI holograms, especially to the amplitude coefficients which are Laplace distributed. The results also indicate that a separation of the wavefront into a speckle field and a remainder representing the macroscopic shape would be advantageous.

Current work is aimed at designing a compression algorithm based on these results. An efficient filter separating the speckle field from the rest of the hologram based on a max-likelihood algorithm is under investigation. Based on a new distortion measure to be designed, we will investigate a rate-distortion theory for Fresnel propagated and wavelet analyzed complex-valued wavefronts. Finally, we will design and implement a rate allocation algorithm and a corresponding compression algorithm.

References:

[1] Wilke, M; Singh, A.K.; Faridian, A.; Richter, T. ; Pedrini, G.; Osten, W. "Statistics of Fresnelet coefficients in PSI holograms", Proc. SPIE 8499, Applications of Digital Image Processing XXXV, 849904 (October 15, 2012); doi:10.1117/12.929745.

[2] Sarker; K. "A Posteriori Rate Allocation for Digital Holograms based on the EBCOT Encoder"; Master Thesis Nr. 3306, Institute of Parallel and Distributed Systems, University of Stuttgart; supervised at the ITO.

Nanometric in-plane displacement measurement using phase singularities

A. K. Singh, G. Pedrini, W. Osten

The measurement of deformations is of great importance for confirming analytical and finite element models, accessing material and device properties, detecting potential defects and determining performance. For some applications, it is necessary to measure deformation with accuracies down to the lower nanometer range.

Phase singularities are present in wave fields reflected or transmitted by an object and are very sensitive to any kind of disturbance, thus by tracking them we may measure small in-plane displacements.

The phase singularities are the zeros of the wave field. Let an analytical signal ψ be written in terms of its real and imaginary parts, ξ, η as

$$\psi(r, t) = \xi(r, t) + i\eta(r, t)$$

the occurrence of singularity requires $\psi = O$; and for that the real and imaginary part of the amplitude ξ, η must be zero. If we draw zero contours of real and imaginary parts of complex amplitude this condition is only satisfied at the intersection of the two contours. As shown in Fig. 1 (green and red lines are the contours of zeros for real and imaginary parts of the complex amplitude respectively) the contours intersect each other at the phase singularities (encircled).

The position of the singularities was determined by using bilinear interpolation allowing the identification of their location with an accuracy of 0.001 pixels. The displacement of any object surface may be obtained by locating the phase singularities before and after the movement.

Experiments were performed to verify the validity of the method. A PZT was used for providing precise displacements and to determine the phase, off-axis digital holography method was used. After locating the coordinates of all the singularities we measured the given displacements as mentioned above. The histograms of the coordinate changes of the phase singularities were plotted and from their maxima we could calculate the displacement in both the directions. As we increase the applied voltage to the PZT for more displacement we have a displacement of the peak location of the histograms describing the shift of a set of singularities. Using the shift of the peak we could calculate the nanometric in-plane displacements. Figure 2 shows the displacements (in nm) as a function of the voltage (in mV) applied to the PZT.

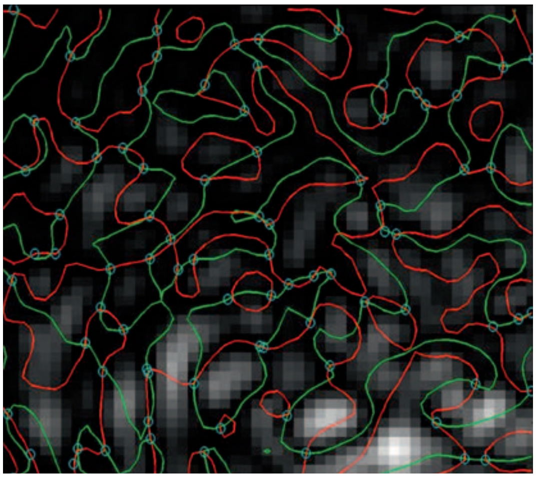

Fig. 1: *Speckle pattern reflected from a diffused object and the corresponding zero contours of real and imaginary part of the complex amplitude.*

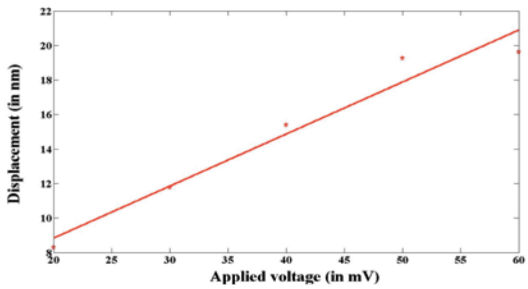

Fig. 2: *Relation between the voltage applied to the PZT and the measured displacement.*

Supported by: DAAD

References:

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Short temporal coherence digital holography with a femtosecond frequency comb laser for optical sectioning

K. Körner, G. Pedrini, I. Alexeenko, W. Osten

Short coherence digital holography with a femtosecond frequency comb laser source may be applied for multi-level optical sectioning. The object shape is obtained by digital reconstructing and processing a sequence of holograms recorded during stepwise shifting of a mirror in the reference arm of a Michelson interferometer [1]–[3].

The used set-up for digital holography with a femtosecond frequency comb laser from MenloSystems is shown in Fig. 1. The laser specifications are as follows: pulse duration 100 fs, $\lambda = 532$ nm, $\Delta\lambda \approx 10$ nm, $\Delta\upsilon_{fc} = 5.994$ GHz (pulse distance in space Y = 50.00 mm), output power ≈ 50 mW. The laser beam is at first expanded and collimated by a telescope and later divided into two parts by a beamsplitter. The reflected and transmitted beams are directed towards the object and a spherical mirror in the reference path, respectively. The wavefronts reflected by the object and the mirror are recombined by the beamsplitter; the CCD camera records the hologram intensity.

The object used for the experimental investigations was a rough metallic cone (see Fig. 2a). Figs. 2.b), c), d) show three numerical reconstructions obtained by using a single hologram with digital focusing in three different planes, each separated by 25.00 mm (Y = 50.00 mm).

Fig. 3 presents the 3-d shape of the cone reconstructed from 17 holograms recorded by displacing the reference mirror by 1 mm between each hologram. The axial resolution is given by the step of the scanning and thus more holograms are needed for improving the accuracy which is limited by the temporal coherence length of one laser pulse that is ≈ 30 µm. The results demonstrate that a set-up based on digital holography using a fs fc-laser can be used for simultaneous multiple optical sectioning.

In the next years, we expect the availability of fc-lasers based on microresonators. In this case, the distance of the sectioning planes can be reduced to approximately 100 µm and will allow applying the optical sectioning method for technical and biological applications in microscopy. Furthermore, by using powerful frequency comb lasers, the multi level optical sectioning method can also be extended to larger objects which may be located far away from the detecting system (airplanes, building or power plant components).

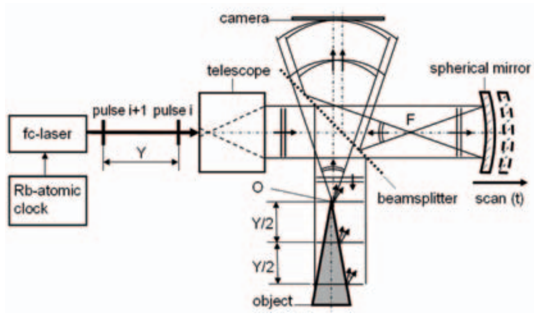

Fig. 1: *Experimental set-up for lensless short coherence digital holography with a fc-laser at 532 nm with a pulse distance in space Y=50.00 mm referenced to a Rubidium atomic clock.*

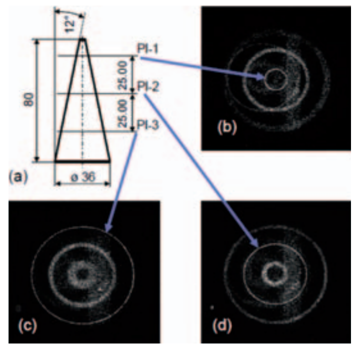

Fig. 2: *a) Schematic of the rough metallic cone used for the investigations, base diameter ≈36 mm, height ≈80 mm, half angle ≈12°. b), c), d) Reconstruction of holograms at three different planes separated by 25.00 mm (Y=50.00 mm).*

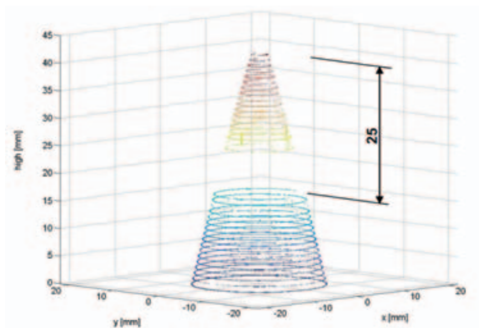

Fig. 3: *Numerical reconstruction of a part of the rough metallic continuous cone.*

References:

[1] Körner, K.; Pedrini, G.; Alexeenko, I.; Steinmetz, T.; Holzwarth, R.; Osten, W. "Short temporal coherence digital holography with a femtosecond frequency comb laser for multi-level optical sectioning", Opt. Express 20, 7237-7242 (2012).

[2] German patent DE 10 2011 016 660 B4 2012.10.25.

[3] Körner, K.; Pedrini, G.; Alexeenko, I.; Lyda, W.; Steinmetz, T.; Holzwarth, R.; Osten, W. "Multi-level optical sectioning based on digital holography with a femtosecond frequency comb laser", Proc. SPIE 8430, 843004 (2012).

Holographic recording of incoherently illuminated or self-luminous objects

D.N. Naik, G. Pedrini, W. Osten

Traditionally, holography requires coherent-light for illuminating the object and recording its 3-D information. However, various attempts have been made to record a hologram of an incoherently illuminated or self-luminous object. In such cases, the light emitted by each point could interfere only with itself and a self-referencing scheme is commonly utilized for recording of the hologram. We adopt an approach based on statistical optics to describe the process of recording of an incoherent-object hologram as a complex spatial coherence function. The principle behind the proposed scheme is based on van Cittert-Zernike theorem. We demonstrate its implementation using a Sagnac radial shearing interferometer for field correlation and a Pockels cell for phase shifting and quantifying the coherence function.

Here the object being recorded is a negative transparency of numeral 3 illuminated by an LED Luxeon Star LXHL-MMID, having spectral width at half maximum of about 35nm at wavelength 530 nm. As shown in Fig. 1, the field distribution at the back focal plane of lens L1 is directed into a properly designed common-path Sagnac radial shearing interferometer. A telescopic system with magnification $\alpha = f_3/f_2 = 1.067$, formed by lenses L2 and L3, introduced inside the interferometer gives a radial shear between the counter propagating beams as they travel through interferometer. The Pockels cell (PC) introduces a phase shift between the orthogonally polarized radially sheared beams. One of the interferograms recorded with an 8-bit CCD (Hitachi KP-2FA) is shown in Fig. 2(a). The fringe contrast and the fringe phase that jointly represent the complex spatial coherence function are shown in Figs. 2(b) and 2(c) respectively. For the reconstruction of the object, this complex spatial coherence function is back propagated. The intensities of the reconstructed object at z=–1mm, z=0mm and z=1mm planes are shown in Figs. 3(a-c) respectively. The corresponding phase distributions that help to focus different sections of the object through propagation are shown in Figs. 3(d-f).

3-D object reconstruction can be achieved even in outdoor environment due to the inherent stability provided by the common path interferometer. Due to the implementation of phase shift using a Pockels cell, the system is mechanics free and has a potential for automated fast measurement applicable to dynamic situations.

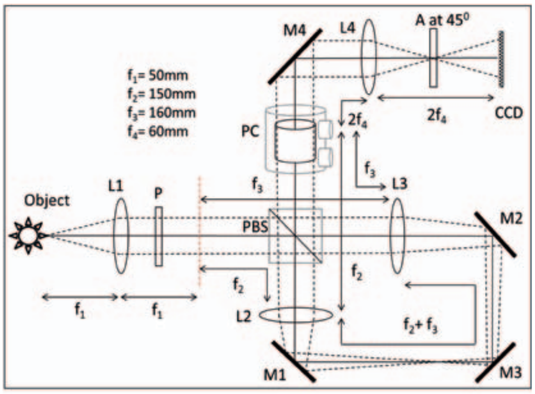

Fig. 1: *Experimental set up for recording the hologram as complex spatial coherence function.*

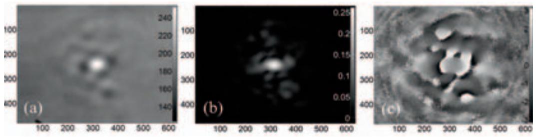

Fig. 2: *(a) One the interferograms recorded by phase shift using Pockels cell. (b) Fringe contrast and (c) Fringe phase jointly representing the complex spatial coherence function at the back focal plane of Lens L1.*

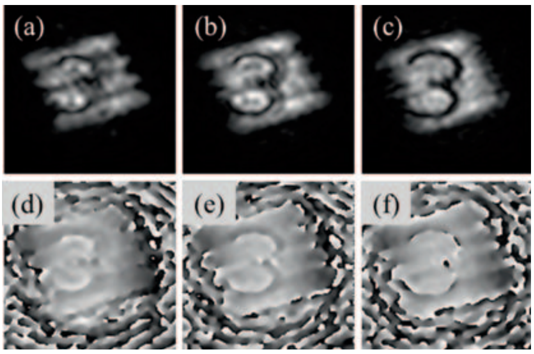

Fig. 3: *(a) ,(b) and (c) show the amplitude of the complex spatial coherence function back propagated to z=–1mm, z=0mm and z=1mm respectively.(d),(e) and (f) show the corresponding phase distribution.*

Supported by: Alexander von Humboldt foundation

References:

[1] Naik, D.N.; Pedrini, G.; Osten, W. "Recording of incoherent-object hologram as complex spatial coherence function using Sagnac radial shearing interferometer and a Pockels cell", Opt. Express 21, 3990-3995 (2013).

Phase retrieval with resolution enhancement by using random-phase illumination

P. Gao, G. Pedrini, W. Osten

Phase retrieval with resolution enhancement is obtained by using random-phase illumination generated by a spatial light modulator.

Figure 1(a) shows the setup used for phase retrieval. The light from a laser diode is expanded by the telescope system L_1–L_2, and is then directed to the spatial light modulator (SLM). The random patterns on SLM (see Fig. 1(b)) are projected to the sample plane by the relaying system (L_3–MO_1). The object wave is magnified by the objective MO_2 and the lens L_4. Then, the diffraction patterns (see Fig. 1(c)) are recorded by a CCD camera, which has a certain distance from the image plane IP of the specimen. Note that the SLM enables to project different random-phase patterns without mechanical movement.

For reconstruction, the complex amplitudes of the M random-phase fields are measured in advance and denoted with A^{k}_{illum}, and k=1,2,…M. we denote with I^{k} the diffraction patterns of the object wave under A^{k}_{illum}. Then, the phase retrieval is performed with the following steps: (1) multiply the amplitude the kth diffraction pattern with a random initial phase factor exp(iφ^{k}), (2 propagate $\sqrt{I^{k}}$ exp(iφ^{k}) to the object plane, (3) the calculated wave is divided by the kth illumination amplitude A^{k}_{illum}, and multiplied by the (k+1) th illumination amplitude A^{k+1}_{illum}, (4) propagate the newly-obtained object wave to the CCD plane, (5) replace the amplitude of the obtained object wave with $\sqrt{I^{k+1}}$. (6) repeat the iteration loop (2)–(5) by using k+1 instead of k, until the difference between two neighbouring reconstruction is smaller than the preset value. Furthermore, the object waves reconstructed from different groups of random-phase illuminations are averaged in order to reduce the noise.

Random-phase illumination can be seen as a superposition of plan waves, which shifts the specimen spectrum in different directions in the Fourier plane. Some of the high frequency components (see the four black dots in Fig. 2(a)), which are beyond the system aperture and cut under on-axis plane wave illumination, can pass through the system. Thus, the random phase illumination can improve the resolution of the optical system, compared with the on-axis plane wave illumination.

To test the resolution enhancement, a transparent structured plate was used as specimen. The images reconstructed by using digital holographic microscopy (DHM) and the phase retrieval method are given in Fig. 2(b) and Fig. 2(c), respectively. Note that DHM is constructed by introducing an additional reference wave. When compare Fig. 2(b) and Fig. 2(c), the resolution improvement by the random-phase illumination can be seen, and the quantity of the resolution enhancement depends on the maximum angle of the random-phase illumination waves. Furthermore, the random-phase illumination eliminates the stagnation problem in the phase retrieval process.

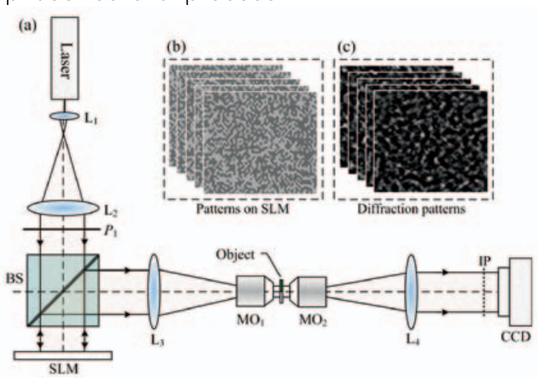

Fig. 1: *(a) Experimental setup of phase retrieval. (b) Illumination patterns loaded on SLM; (c) generated diffraction patterns on CCD camera.*

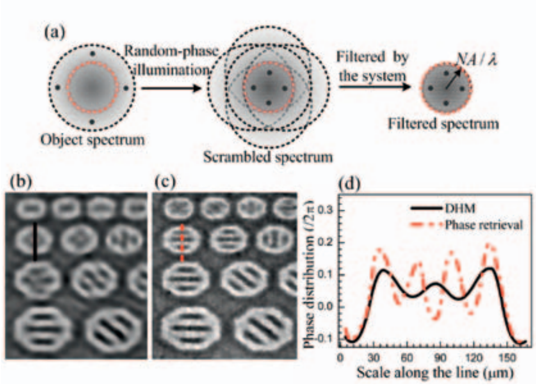

Fig. 2: *Resolution enhancement of phase retrieval with random-phase illumination; (a) Schematics of resolution enhancement; (b) and (c) reconstructed phase images by the DHM with plane wave illumination and the phase retrieval with random-phase illumination; (d) phase distribution along two lines in (b) and (c).*

Supported by: Alexander von Humboldt foundation

Structured illumination for resolution enhancement and autofocusing in digital holographic microscopy

P. Gao, G. Pedrini, W. Osten

Resolution enhancement and autofocusing in digital holographic microscopy (DHM) is obtained by using structured illumination generated by a spatial light modulator.

Figure 1(a) shows the setup used for our investigations. The light from a laser diode is expanded by the telescope system L_1–L_2, and is then directed to the spatial light modulator (SLM). The light modulated by the SLM is projected to the sample plane by the relaying system (L_3–L_4). The specimen is placed in a half of the sample plane, while the other free half is used as reference. After diffraction by a Ronchi grating, these two halves go along two different diffraction orders via a telescope system L_5–L_6, and overlap with each other in the CCD plane. The quasi common path of the object and reference beams enables to use the low-coherence laser diode as light source to reduce the coherent noise.

Four binary phase gratings rotated by m×45° see Fig. 1(b) are loaded sequentially on one half of the SLM, the other half has no structure and is used as a reference. For each orientation the phase grating loaded on the SLM is shifted three times by nδ. The shifting of the pattern is useful for reconstructing the object waves and synthesizing a large aperture. Note that the SLM enables to project fringes of different orientations and phase shift without mechanical movement.

Due to the tilted reference wave the spectrum of the generated hologram has a central term and two side lobes (see Fig. 1(c)). By selecting one lobe of the spectrum of the hologram, the wave at a distance Δz from the detector can be reconstructed. The reconstructed wave can be further decomposed into three waves $A_{m,-1}$, $A_{m,0}$ and $A_{m,1}$ along the –1st, 0th and +1st diffraction orders of the illumination wave. Then, the synthetic aperture is obtained by combination of the spectra of the waves $A_{m,-1}$, $A_{m,0}$ and $A_{m,1}$. Finally, by an inverse Fourier transform of the synthetic spectrum, a focused image with enhanced resolution is retrieved, as is shown in Fig. 2.

The structured illumination can also be used to determine the focus plane. Structured illuminations can be regarded as a superposition of plane waves, which carry the specimen replicas through different paths before overlapping in the focus plane. Thus, the image plane is numerically determined by searching for the minimal deviation between the reconstructed images carried by different diffraction orders of the structured illuminations. By using this method, the image plane of the specimen is determined, and results are given in Fig. 3.

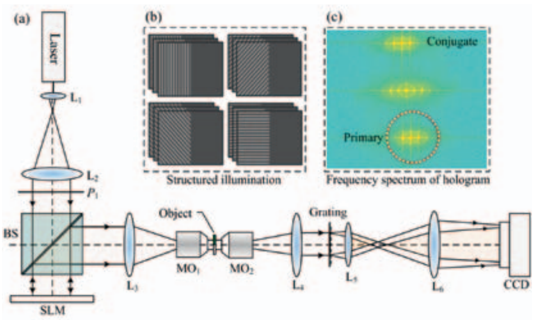

Fig. 1: *(a) Schematics of the DHM setup. (b) four group of structured illuminations with different directions; (c) Frequency spectrum of the generated hologram.*

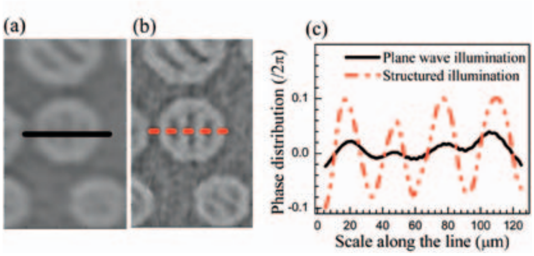

Fig. 2: *Experimental results for resolution enhancement; (a) and (b) reconstructed phase images by using plane wave illumination and structured illumination; (c) the phase distributions along the two lines drawn in (a) and (b).*

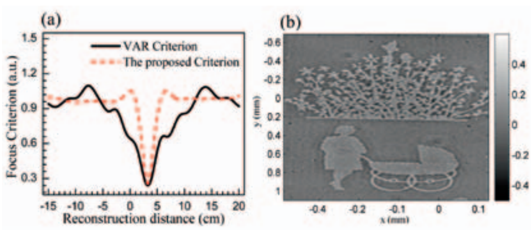

Fig. 3: *Experimental results for autofocusing; (a) focus criterions by amplitude variation criterion (VAR) and the proposed method; (b) reconstructed phase (radiants/2π) with Δz=3.2cm.*

Supported by: Alexander von Humboldt foundation

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Optical Design and Simulation

Application of complex surfaces in modern optical design

A. Herkommer, C. Pruß, R. Reichle

There is a rapidly growing interest in the employment of complex surfaces within optical systems. Examples of such surfaces are diffractive surfaces, facetted surfaces and freeform surfaces. Consequently modern optical design must sharpen its tools in order to properly handle these surfaces during modelling and optimization, and also to keep track with technological developments in the fabrication and testing of such surfaces:

For example recent lithographic technologies allow for the fabrication of high period diffractive structures on planar and curved optical surfaces with high precision. Such diffractive surfaces offer the optical designer extra degrees of freedom, which are of special importance for optical systems, where light collection efficiency is important [1]. In Fig. 1 we illustrate an eyepiece design, which could considerably be improved by a diffractive surface on the backside of a curved lens. For these hybrid design classes it is mandatory to include the realistic as-built performance of the employed diffractive elements into the design phase [2]. Correspondingly, we at the ITO, develop simulation techniques to include fabrication specific diffraction efficiencies and stray light into the optimization and evaluation process.

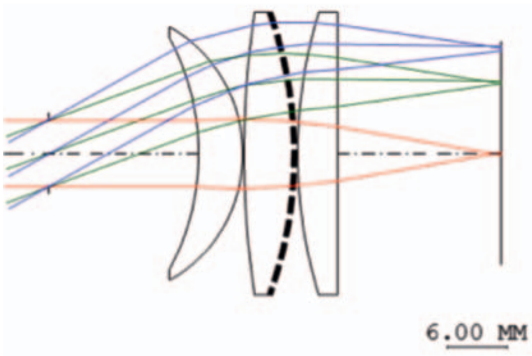

Fig. 1: *Hybrid eyepiece design with a diffractive surface on the back-side of the second lens.*

Stray-light and fabrication issues are also crucial for another class of complex surfaces, which are mainly used in illumination design: Fresnel surfaces. Figure 2 shows a design study of a solar concentrator optics for high efficient solar cells. A Fresnel lens is used as a primary element in order to concentrate the light into the secondary optics. The design of such Fresnel optics is mainly limited by the fabrication process, the achievable efficiency and maximum period of the element.

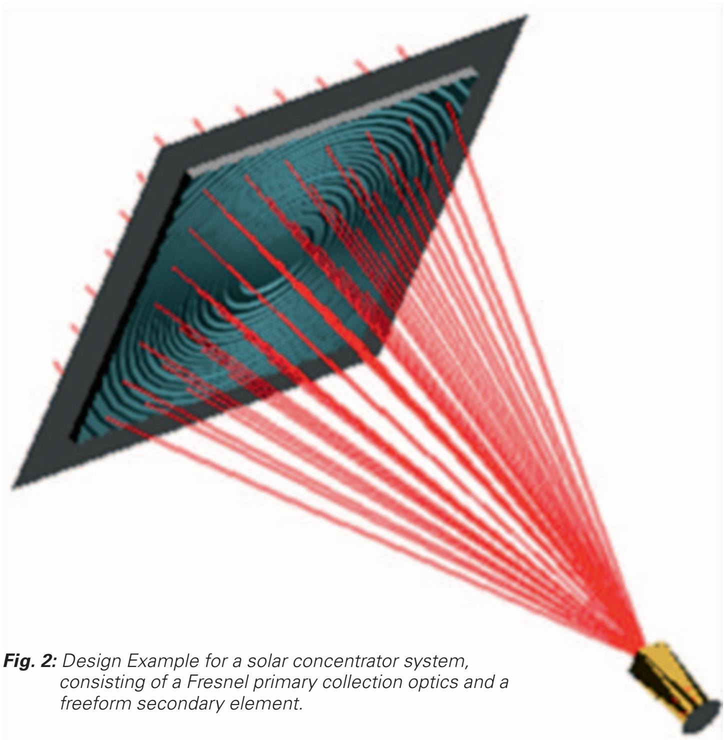

Fig. 2: *Design Example for a solar concentrator system, consisting of a Fresnel primary collection optics and a freeform secondary element.*

This illumination example also introduces the third class of complex surfaces, which is of rapidly growing interest: The secondary optics in Fig. 2 can be a freeform optical element. Freeform surfaces are today discussed and employed in various kinds of illumination and imaging optical systems. In consequence methods for the design, the surface description and the fabrication and testing of such components need to be developed, as illustrated in Fig. 3.

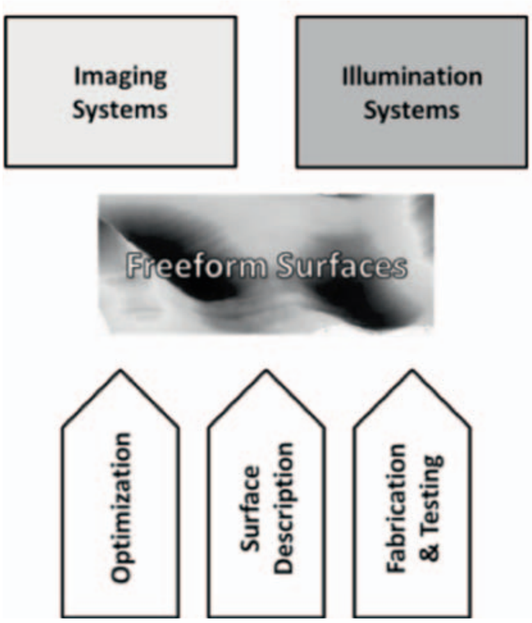

Fig. 3: *Illustration of the interdependence of freeform optical surfaces to the design, surface description and fabrication.*

At the ITO research is currently performed and planed in all three areas: During design the main problem is to be in control of the many degrees of freedom during optimization. A proper surface description is required in order to allow for an efficient optimization and an exact fabrication. Fabrication of freeform surfaces however is only possible is an adequate testing is available.

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Phase space methods in geometrical optics

D. Rausch, A.M. Herkommer

In optical design especially in illumination design, the transport of radiance through the system is important. Typically used components in illumination design affect the spatial as well as the angular distribution. Therefore it is reasonable to use a description where angle and position can be illustrated simultaneously. The phase space concept provides an interesting access towards the radiometric quantities. Within an optical system a single ray is defined by its position and angle in space. Therefore every single ray propagating through the system can be associated with a point in phase space. Thus ray-tracing corresponds to a trajectory in phase space [1].

A light source occupies a certain angular and spatial extend witch is a 4 dimensional volume in phase space called etendue. The flux per entendue is the radiance distribution L (x, u) as depicted in Fig. 1. The projection of the radiance to the angular or the spatial axis in phase space allows the calculation of the intensity I (u) and the irradiance E (x).

An analysis of the phase space transformation introduced by optical components provides an entire picture of the optical functionality. Paraxial free propagation corresponds to a shear of the phase space whereas propagation from the front to the back focal plane of a thin lens causes a rotation by 90 degree. Reflection on surfaces leads to a back-folded and mirrored distribution in phase space.

Integrator rods and double arrays are commonly used components in illumination design. Therefore it is of special interest to investigate these elements within the phase space picture [2].

Integrator rods mix the incoming light distribution resulting in a homogenization of the irradiance at the exit of the rod. The incoming light is reflected at the sidewalls of the rod leading to a segmentation of the phase space distribution Fig. 2c).

Optical arrays separate the incoming light in channels due to the apertures of the microlens. Different channels are superimposed at the target plane. Fig. 3 shows the phase space distribution at the target plane after a double array and an integrator lens. The effect is similar to the rod a homogenization in position and segmentation in angle.

The analysis of illumination components in phase space offers another access besides classical ray-tracing.

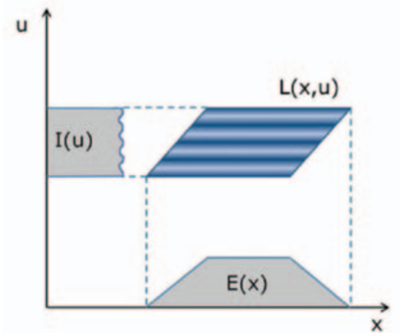

Fig. 1: *Phase space illustration of the radiance L (x, u), intensity I (u) and irradiance E (x).*

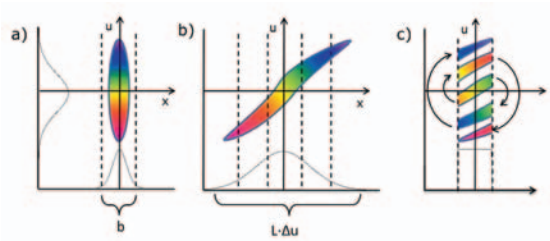

Fig. 2: *a) Initial distribution at the entrance of a rectangular integrator rod. b) Distribution after free propagation of the length of the rod. c) Final distribution at the exit of the rod.*

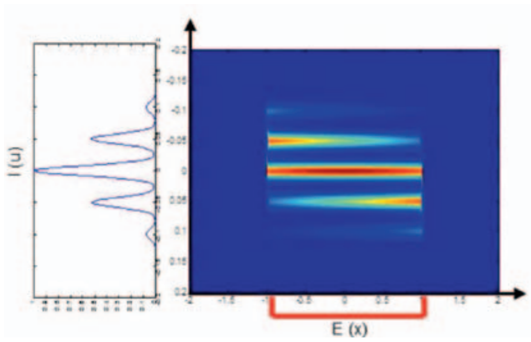

Fig. 3: *Phase space distribution after propagation through a double array and an integrator lens, leading to a constant irradiance E(x) und a discrete intensity I (u).*

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Hybrid endoscopic zoom system with integrated tomographic sensor

S. Thiele, A. Herkommer

As a part of the Baden-Württemberg Stiftung project "Hybride optische Technologien für die Sensorik", this work aims at the development of a miniaturized zoom system which combines both, imaging and tomography. In this joint research project our project partner IMTEK (University of Freiburg) is improving and developing microoptical components, while the work at the ITO is focused onto the optical system design.

Extensive research effort has been put on the development of miniaturized active optical elements, such as tunable membrane lenses or micromirrors. The current technology allows the construction of small integrated active optical systems based on a modular approach (Fig. 1) [1]. As a more complex device, the conceived hybrid sensor system requires a sophisticated and well balanced optical design.

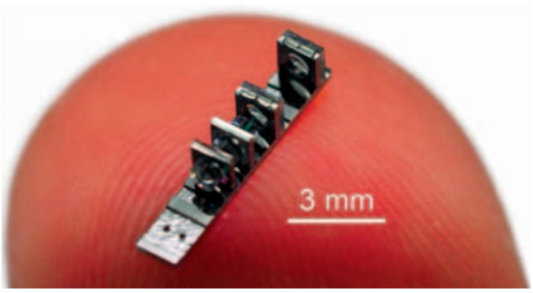

Fig. 1: *Technology example showing the state of the art. Most of the single components are fabricated by micromachining processes (picture delivered by project partner).*

Figure 2 shows the latest concept with a system diameter of below 2 mm. It comprises two membrane lenses, which can be tuned independently in radius of curvature by applying an external fluid pressure. This enables zooming and focusing without mechanical parts at a high level of integration. Additionally to the imaging beam path which creates an image on the CMOS sensor chip, the system contains a second beam path for optical coherence tomography (OCT). A MEMS scanning mirror in side-looking configuration enables a laterally resolved OCT signal as well as an extension of field of view for the imaging part. Additional components such as diffractive optical elements (DOE's) or aspheres can compensate for static aberrations.

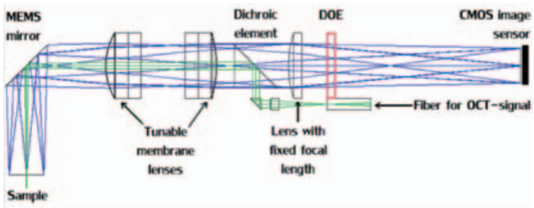

Fig. 2: *Example for the current concept within the raytracing software ZEMAX.*

In order to narrow down the parameter space, the concept has been modelled paraxially as well as within a raytracing software. Realistic lens profiles, obtained by finite element simulations and tactile measurements have been implemented (Fig. 3). The setup allows a systematic investigation with an automatic optimization in terms of the two lens pressures. Different parameters, such as wavefront errors or vignetting factors can be plotted as a function of working distance and magnification, allowing an evaluation of the expectable optical performance. Due to small numerical apertures given by the system, diffraction is limiting the achievable imaging resolution to ~2 µm. This is sufficient to resolve the most relevant features in common endoscopy inspections.

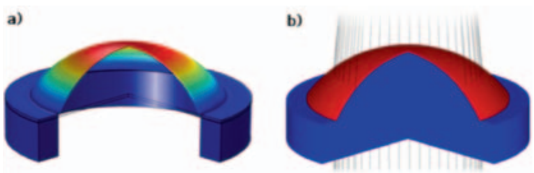

Fig. 3: *a), finite element simulation of a membrane lens with a diameter of 1 mm. b), corresponding surface model (4th order polynomial) implemented in ZEMAX.*

Supported by: Baden-Württemberg Stiftung
Project: "Hyazint"
Cooperation: Gisela-und-Erwin-Sick-Lehrstuhl für Mikrooptik, Institut für Mikrosystemtechnik (IMTEK), Universität Freiburg

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From Analog to Digital Holography. What is the Benefit?

Sensor and Test Conferences 2011, Nürnberg 2011

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ICO-22, Puebla, Mexico 2011

W. Osten:

How to overcome physical limitations in optical micro and nano metrology.

10th International Conference „Correlation Optics", Chernivtsy, Ukraine 2011

W. Osten:

What Optical Metrology can do for Experimental Mechanics?

International Conference on Advances in Experimental Mechanics: Integrating Simulation and Experimentation for Validation (ISEV), 1st joint SEM and BSSM conference, Edinburgh 7-9 September 2011

W. Osten:

Optical micro and nano metrology: limitations and solutions.

EOS Topical Meeting "Micro- and Nano-Optoelectronic Systems", Bremen, Dec 7-9, 2011

W. Osten:

Prospects and Challenges for the Optical Inspection of Micro- and Nano-Structures.

Micronarc Alpine Meeting MAM 2012, Villars-sur-Ollon, Suisse, Jan 2012

W. Osten:

How to bring your Laboratory in the Cloud? (About the Future of Remote Metrology).

Optimess 2012, 5. International Conference on Optical Measurement Techniques, Antwerp, April 4-5, 2012

W. Osten:

Optical Multi-Scale 3D-Metrology or another Kind of Sensor Fusion.

International PTB Summer School of Metrology, Burg Warberg, May 2012

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HoloMet 2012, Utsunomiya, Japan, July 2012

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Remote Laboratories for Optical Metrology: From the Lab to the Cloud.

Speckle 2012, 5. International Conference on Speckle Metrology, Vigo, Spain, 10-12 Sept. 2012

W. Osten:

Inverse Problems in Optical Metrology: Exemplary Solving Strategies.

Chinese-German Binational Workshop on Inverse Problems, Sarbrücken, 8. – 12. Oct. 2012

W. Osten:

Model-based reconstruction of periodic sub-λ features.

Leibniz-Konferenz "Sensorsysteme 2012", Lichtenwalde, 18.10. - 19.10.2012

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H. Tiziani

Chandra S. Vikram Award 2012, SPIE

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Statistics of Fresnelet coefficients in PSI holograms

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Patents

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Verfahren zur optischen Kompensation der Maßspurdezentrierung bei Drehwinkelsensoren / Device and method for optically compensating for the measuring track decentralization in rotation angle sensors

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family patent applications: WO 2011029587 A1,
CN 102483336 A, US 20120168615 A1, EP 2475966 A1,
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Date of publication: 2011.03.17

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Hopp, David; Wibbing, Daniel

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Date of publication: 2012.03.15
Assignee: Festo AG & Co. KG, Esslingen

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Verfahren und Anordnung zur Kurz-Kohärenz-Holografie / Method and arrangement for short coherence holography

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Inspection for lithography

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Verfahren und Anordnung zur robusten Interferometrie

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Date of publication: 2011.03.10

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Method and arrangement for a rapid and robust chromatic confocal 3d measurement technique

JP 4908524 B2
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Assignee: Sirona Dental Systems GmbH

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Justage einer zu prüfenden optischen Fläche in einer Prüfvorrichtung

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Verfahren zur optischen Kompensation der Maßspurdezentrierung bei Drehwinkelsensoren

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Verfahren und Anordnung zur Kurz-Kohärenz-Holografie

DE 102011016660 B4
Date of publication: 2012.10.25

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Doctoral thesis 2011–2012

Schwab, Xavier

Vergleichende Digitale Holographie: Nulltest-Interferometrie für raue Oberflächen

11/2011

Wiesendanger, Tobias

Defektindikatoren in der multiskaligen optischen Messtechnik

2/2012

Hopp, David Maximilian

Inkrementale und absolute Kodierung von Positionssignalen diffraktiver optischer Drehgeber

4/2012

Berger, Reinhard

Zum Einfluss der Probentopografie auf die Messunsicherheit bei der Weißlicht-interferometrie

5/2012

Diploma thesis 2011–2012

Gronle, Marc

Untersuchung zur Realisierung eines chromatisch lateral aufgespalteten Spektralinterferometers

6/2011

Tarbeyevskaya, Alena

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7/2011

Dilger, Matthias

Construction and analysis of a new laser teaching system

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Thiel, Christian

Fringing-field Effekt bei hochauflösenden LCoS-Modulatoren

2/2012

Nguyen, Huyen Trang

Untersuchungen zur Erweiterung des Tiefenmessbereichs in einem lateral aufgespaltenen Spektralinterferometer

2/2012

Schaub, Christian

Verbrennungsanalyse mittels 2-Farben Methode am optisch zugänglichen Ottomotor

9/2012

Wagner, Heiko

Ultraschnelle digital-optische Interferometrie

12/2012

Student research thesis 2011–2012

Thiel, Christian

Design und Konstruktion eines SLM basierten Mikroskops

2/2011

Tarbeyevskaya, Alena

Modellierung und Simulation eines konfokalen Mikroskops zur Analyse und Bewertung von Fehlerquellen

3/2011

Fleer, Michael

Holografische Laservibrometrie – Hologrammberechnung und Optimierung des Aufbaus eines SLM-basierten Multipoint Vibrometers

3/2011

Wagner, Heiko

Design und Kalibrierung eines Shack-Hartmann Sensors

3/2011

Nguyen, Huyen Trang

Auslegung und Konstruktion eines Autofokussystems für einen Laserdirektschreiber

7/2011

Wang, Mi

Optimierung in der Bildverarbeitung

12/2011

Alexeyenko, Olena

Digitale Holographie im UV-Bereich für die Untersuchung von Zellen

5/2012

Illg, Christian

Positionsbestimmung durch latente Bilder in Fotolack

5/2012

Cheng, Qifeng

Formmessung von rauen Objekten mit 2 Wellenlängen digitaler Holographie

8/2012

Lucke, André

Entwicklung eines Subpixel-Algorithmus zur adaptiven Kantendetektion

8/2012

Liu, Xuefeng

Untersuchung eines neuartigen Ansatzes zur Steigerung der Genauigkeit triangulationsbasierter Verfahren

10/2012

Sabbagh, Ahmed

Konstruktion eines multifunktionalen digitalholografischen Mikroskops

10/2012

Fink, Florian

Vertikaler Differentieller Interferenzkontrast

10/2012

Angold, Paul

Design eines Topografiesensors auf Basis der makroskopischen Streifenprojektion

12/2012

Baumann, Daniel

Proximity Korrektur für die Herstellung von Blaze-Gitter mit Laserdirektbelichtung

12/2012

Schlichenmaier, Pascal

Optische Kompensation des Dezentrierungsfehlers bei Drehwinkelsensoren

12/2012

Optik-Kolloquium 2011

Mikro- und Nanooptik: Design, Herstellung, Prüfung und Anwendung

am 23. Februar 2011, Teilnehmer: ca. 200

Begrüßung und Einführung	Prof. Dr. W. Osten *ITO, Universität Stuttgart*
Mikrooptik als Schlüsseltechnologie: Von der DUV Lithographie zur Wafer-Level Kamera	Dr. R. Voelkel *SUSS MicroOptics SA, Neuchatel, Schweiz*
Planar-integrierte Mikrooptik: Entwurf, Fertigung, Anwendungen	Prof. Dr. J. Jahns *Lehrgebiet Optische Nachrichtentechnik, FernUniversität Hagen*
Fourier-Optik in der Integration: Breitstreifen-Halbleiterlaser mit monolithisch integrierten Fourier-optischen Transversalmodenselektoren	Prof. Dr. H. Fouckhardt *AG Integrierte Optoelektronik und Mikrooptik, TU Kaiserslautern*
Durchstimmbare Mikro- und Nanooptik	Prof. Dr. H. Zappe *IMTEK, Labor für Mikrooptik, Universität Freiburg*
Adaptive Mikrooptik für Ultrakurzpuls-Laser	Dr. R. Grunwald *Max-Born-Institut für Nichtlineare Optik und Kurzzeit-Spektroskopie, Berlin*
3D Laser-Lithographie – ein vielseitiges Werkzeug für die Nanotechnologie	Prof. Dr. G. von Freymann *AG Optische Technologien und Photonik, TU Kaiserslautern*
Perspektiven für die Subwellenlängen-Mikrooptik: Design, Herstellung und Anwendung	Dr. E.-B. Kley *Institut für Angewandte Physik, Friedrich-Schiller-Universität Jena*
Neue Fertigungstechnologien zur Herstellung diffraktiver Optiken mittels Laser-Lithographie	M. Häfner *ITO, Universität Stuttgart*
Inspektionskonzepte für die Detektion von Mikro/Nano-Defekten in großflächigen Strukturen	Dr. K. Gastinger *SINTEF ICT Optical Measurement Systems and Data Analysis, Trondheim, Norwegen*
3D-Metamaterialien	Prof. Dr. H. Giessen *4. Physikalisches Institut, Universität Stuttgart*
Superlinsen durch Metamaterialien: Visionen und Möglichkeiten	P. Schau *ITO, Universität Stuttgart*
Aktive Mikrooptik zur ortsaufgelösten Steuerung des Polarisationszustandes	F. Schaal *ITO, Universität Stuttgart*

Optik-Kolloquium 2012

Optikdesign und Simulation: Innovative Methoden und Systeme

am 22. Februar 2012, Teilnehmer: ca. 200

Begrüßung und Einführung	Prof. Dr. A. Herkommer und Prof. Dr. W. Osten *ITO, Universität Stuttgart*
Freeform surfaces – hype or handy design tool?	Wilhelm Ulrich *Carl Zeiss, Oberkochen*
Optische Freiformflächen – von Design und Modellierung bis zur Anwendung	Prof. Dr. Stefan Sinzinger *Institut für Lichttechnik und Technische Optik, TU Ilmenau*
Flachbauende Multiaperturabbildungsoptiken	Dr. Andreas Brückner *Fraunhofer IOF, Jena*
Simulation der Fokussierung ultrakurzer optischer Pulse mit optischen Systemen sehr hoher numerischer Apertur	Prof. Dr. Norbert Lindlein *Lehrstuhl für Optik, Universität Erlangen*
From ray to field tracing	Prof. Dr. Frank Wyrowski *Institut für Angewandte Physik, Friedrich-Schiller-Universität Jena*
Effizientes Beleuchtungs-Design mit Hilfe von Differentialgeometrie	Prof. Dr. Peter Ott *Technische Optik und Konstruktion, Hochschule Heilbronn*
Maßschneidern – eine Designmethode speziell für Beleuchtungsdesign	Prof. Dr. Harald Ries *OEC AG, München*
LEDs von innen gesehen Wafer-Level Kamera	Dr. Julius Muschaweck *Osram AG, Augsburg*
Entwicklung eines hochauflösenden Hochgeschwindigkeits-Röntgen-Videosystems zur Charakterisierung von Laserschweißvorgängen	Dr. Siegfried Nau *Fraunhofer EMI, Freiburg*
Diffraktive Elemente in lichtstarken bildgebenden Messsystemen	René Reichle *ITO, Universität Stuttgart*
Anwendungsmöglichkeiten für GPU-beschleunigtes Raytracing	Florian Mauch *ITO, Universität Stuttgart*

Optik-Kolloquium 2013

Optics for Space (Optische Technologien zur Erforschung des Weltraums)

am 27. Februar 2013, Teilnehmer: ca. 150

Begrüßung und Einführung	Prof. Dr. W. Osten *ITO, Universität Stuttgart*
Beobachten wie aus dem Weltraum: Adaptive Optik für Sonnen-Teleskope	Prof. Dr. O. von der Lühe *Kiepenheuer-Institut für Sonnenphysik, Freiburg*
Ultrapräzise Metallspiegel mit exzellenter Form und Rauheit für Astronomie und Raumfahrt	Dr. S. Risse *Fraunhofer-Institut für Angewandte Optik und Feinmechanik, Jena*
NIRSpec – Ein IR Spektrometer für das James Webb Teleskop	Dr. W. Holota *Holota Optics, Bad Tölz*
Astronomische Polarimetrie	Prof. Dr. C. U. Keller *Leiden Observatorium, Universität Leiden, Niederlande*
SOFIA - Ein fliegendes Observatorium	Prof. Dr. J. Wagner *Deutsches SOFIA Institut, Universität Stuttgart*
Infrarot-Astronomie mit SOFIA	Dr. B. Stecklum *Thüringer Landessternwarte Tautenburg, Karl-Schwarzschild-Observatorium, Jena*
eROSITA – Eine neue Himmelsdurchmusterung im Röntgenbereich	Dr. P. Predehl *Max-Planck-Institut für extraterrestrische Physik, Garching*
LISA: Laser-Interferometrische Gravitationswellen Weltraum-Antenne	Dr. G. Heinzel *Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Inst.), Hannover*
Optische Intersatelliten-Datenübertragung: das Tesat Laser Communication Terminal	Dr. F. Heine, Dr. H. Zech *Tesat-Spacecom GmbH & Co. KG, Backnang*
Polarisations-Scrambler auf Basis von Metamaterialien für Weltraumanwendungen	Ph. Schau *ITO, Universität Stuttgart*
Modale Regelung verformbarer Sekundärspiegel für erdgebundene Teleskope	Dr. T. Ruppel *Corporate Research and Technology, Carl Zeiss AG, Jena*
Wellenfront-Sensorik für die Erfassung hochfrequenter Störungen	S. Dong *ITO, Universität Stuttgart*

Organized international conferences: 2011 – 2012

W. Osten, M. Kujawinska, P. Ferraro:

SPIE Congress Optical Metrology Conference 2011

May 22 – 26, 2011, Munich, Germany

W. Osten, N. Reingand:

"Industry meets Academia"

SPIE Workshop, May 22, 2011, Munich, Germany

P. Lehmann, W. Osten, K. Gastinger:

Optical Measurement Systems for Industrial Inspection VII

SPIE Congress, May 22 – 26, 2009, Munich, Germany

C. Gorecki, A. Asundi, W. Osten:

Optical Micro- and Nanometrology IV

April 16 – 18, 2012, Brussel, Belgium

T. Yatagai, W. Osten:

HoloMet 2012

4th International Workshop on Advanced Imaging and Metrology, July 24 – 26, 2012, Utsunomiya, Japan

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